Tephra clean-up in Auckland City, New Zealand: quantitative impact assessment and response planning

A thesis
submitted in partial fulfilment of the requirements
for the degree of
Master of Science in Hazard and Disaster Management
at the
University of Canterbury
by

Josh Hayes

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Department of Geological Sciences
University of Canterbury
New Zealand

2014

Frontispiece

The isthmus of Auckland with it's extinct volcanoes, by Dr. Ferdinand von Hochstetter 1859

Gotha: Justus Perthes, 1865. In: Hochstetter and Petermann, Geological and topographical atlas of New Zealand: six maps of the provinces of Auckland and Nelson. Auckland: Delattre, 1864. Map 3.

Abstract

Tephra impacts urban communities by disrupting transport systems, damaging buildings and infrastructure, and affecting human health. Impacts can be exacerbated by remobilisation of tephra by wind and water processes, and human activities. Therefore, prompt and effective tephra clean-up measures are a fundamental component of the societal response to tephra fall. However, planning for tephra clean-up operations is rare which increases losses and prolongs recovery. To support effective planning knowledge gaps need filling, such as determining tephra volumes requiring removal, methods of clean-up, and potential disposal sites.

The objectives of this thesis are to build an evidence base of tephra clean-up operations which can be used to inform an assessment of the potential impacts of tephra clean-up operations in Auckland, New Zealand. To achieve this, I have reviewed case studies of tephra clean-up operations spanning 50 years and from around the world. This forms the most comprehensive existing evidence base for tephra clean-up operations. This review can inform impact assessments and response planning by documenting methods involved in tephra clean-up and by assessing a range of empirical relationships between tephra accumulation and clean-up metrics such as collected tephra volume, costs, and the duration of operations. Large variation is seen between communities that have little or no prior tephra clean-up experience, which indicates that relatively simple tephra accumulation-cost relationships are unlikely to provide sufficient results for impact assessments. Clean-up experiences and costs are context specific and depend on many community-specific attributes. However, one relationship consistent across all case studies describes the percentage volume of tephra collected related to tephra fall accumulation in the urban area. Urban areas which experienced low tephra accumulation (1,000 m^3/km^2 or 1mm thickness) only remove 1% of the total deposit, whereas urban areas which experienced large accumulations (>50,000 m^3/km^2 or 50 mm thickness) remove up to 80% of the deposit. This relationship can inform impact assessments by providing an estimate of the likely response for a given tephra fall. This information, used in conjunction with community specific characteristics, allows communities to create

more robust plans for tephra fall clean-up activities.

Using the compiled evidence base as a guide, I have developed a tephra clean-up model using geospatial analysis and monte carlo simulation methods to assess duration and costs of tephra clean-up in Auckland after distal and proximal volcanic eruptions. The model suggests that clean-up duration could take weeks to months to clean-up tephra fall deposits, and potentially years to clean-up areas impacted by pyroclastic flows. Costs will range from a few hundred thousand dollars to implement street sweeping clean-up operations of road surfaces to hundreds of millions of dollars to clean-up areas impacted by pyroclastic flows. These results have implications for response (e.g. resource requirements, disposal site locations) and recovery (e.g. restoration of land for use, retirement of land) planning as part of disaster risk reduction in Auckland.

UC UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Deputy Vice-Chancellor's Office
Postgraduate Office

Co-Authorship Form

This form is to accompany the submission of any thesis that contains research reported in co-authored work that has been published, accepted for publication, or submitted for publication. A copy of this form should be included for each co-authored work that is included in the thesis. Completed forms should be included at the front (after the thesis abstract) of each copy of the thesis submitted for examination and library deposit.

Please indicate the chapter/section/pages of this thesis that are extracted from co-authored work and provide details of the publication or submission from the extract comes:
Chapter 2 - Tephra fall clean-up in urban environments

Please detail the nature and extent (%) of contribution by the candidate:
Mr Hayes wrote the manuscript, analysed data, and made all figures (80%). Dr Thomas Wilson came up with the initial project formation, contributed to development of manuscript and data analysis (15%). Dr Christina Magill provided data and editorial suggestions (5%).

Certification by Co-authors:
If there is more than one co-author then a single co-author can sign on behalf of all
The undersigned certifys that:

- The above statement correctly reflects the nature and extent of the PhD candidate's contribution to this co-authored work
- In cases where the candidate was the lead author of the co-authored work he or she wrote the text

Name: *Thomas Wilson* Signature: Date: *8 December 2014*

Acknowledgements

I wish the show my gratitude to my supervision team: Dr Thomas Wilson, Dr Natalia Deligne, Prof Jim Cole, and Dr Matthew Hughes for showing belief in me. Dr. Thomas Wilson has been a source of never ending enthusiasm. Thank you for including me in collaborative works, being a mentor, and your patience and assistance helping me arrange my thoughts and ideas into something that other people can understand! Dr. Natalia Deligne has been a great source of support, guidance, and always pushed me to go the extra mile! I would like to thank Professor Jim Cole for his noble pursuit of ridding my writing of redundant words! Dr. Matthew Hughes offered many insightful ideas, enthusiasm, and support which is greatly appreciated.

I also wish to acknowledge Dr Carol Stewart (Joint Centre for Disaster Research) and Dr Graham Leonard (GNS Science) for numerous informative discussions over the past 12 months. I would also like to thank Richard Woods and Brodie Rafferty (Auckland Civil Defence) for their assistance and enthusiasm towards this project. Thanks also to Dr Christina Magill (Risk Frontiers, Macquarie University) for collaboration and informative discussions.

To my fellow CoUGARS: Grant Wilson, Heather Craig, Daniel Blake, Daniel Hill, and Rebecca Fitzgerald. Thank you all for your advice, encouragement and discussions!

Thank you to the administrative staff within the Department of Geology. Big thank you to Pat and Janet for you help in dealing with administrative issues!

I would like to thank Mason Trust and DEVORA for financial assistance with this project.

Last but not least, I want to thank my friends and family for their support over the years. Especially to my parents for their "occasional" financial support!!!

Contents

List of Figures

List of Tables

Chapter 1

Introduction

> *Sometimes it does us a power of good to remind ourselves that we live where two tectonic plates meet, in a somewhat lonely stretch of windswept ocean just above the roaring forties. If you want drama you've come to the right place.*
>
> Sir Geoffrey Palmer

1.1 Context of study

Naturally occurring processes such as earthquakes, floods, hurricanes, and volcanic eruptions can become hazards when there is potential for them to negatively impact on society (ISDR, 2009). The occurrence and severity of negative impacts from a hazard are related to the vulnerability of a society (ISDR, 2009). Vulnerability is the characteristics and circumstances of a society that make it subject to the negative impacts of a hazard (ISDR, 2009). Disasters result when there is a disruption to the functionality of a community that exceeds the affected communities ability to cope (ISDR, 2009). The risk of a disaster occurring is related to the probability of a hazardous event occurring and the negative consequences which could result (ISDR, 2009). The risk of disaster has lead societies to conduct activities to analyse and manage factors which can contribute to disasters. Typical activities include implementing or strengthening building codes to reduce the risk of building collapse, or land use planning to reduce the risk of developing on hazard prone land. These activities are known as disaster risk reduction activities (ISDR, 2009).

One negative impact that contributes to a disaster is large volumes of waste being generated in short periods of time by sediment deposition (e.g. floods, tephra fall, landslides) or building and infrastructure damage, which can exceed existing waste management capabilities (Reinhart & McCreanor, 1999). Therefore, disaster waste management needs to be considered within a broad framework of disaster risk reduction (Figure 1.1). Disaster waste management occurs within the readiness (planning), response (operation), and recovery (restoration of urban functionality) phases. The composition of disaster waste (e.g. sediment, rock, construction material, vegetation debris, industrial chemicals) will influence what management options should be taken, and will differ depending on the area impacted (e.g. urban, rural, coastal, vegetated) and type of event which occurs (e.g. earthquake, volcanic eruption, flood). These waste streams have a range of impacts which can manifest immediately (e.g. impede emergency response), in the medium term (e.g. slow recovery) and in the long term (e.g. environmental impacts) (Brown et al., 2011). Immediate concerns for disaster waste management involves removing debris which is impeding emergency response. Such circumstances include debris which is blocking important emergency transport corridors and presenting a health and safety hazard (e.g. unsafe buildings). Medium term considerations involve clearing debris to facilitate the recovery efforts and prevent psychosocial impacts. Long term considerations relate to ensuring that debris disposal will not present a future threat to the environment (Brown et al., 2011). This shows disaster clean-up is an integral aspect to disaster risk reduction.

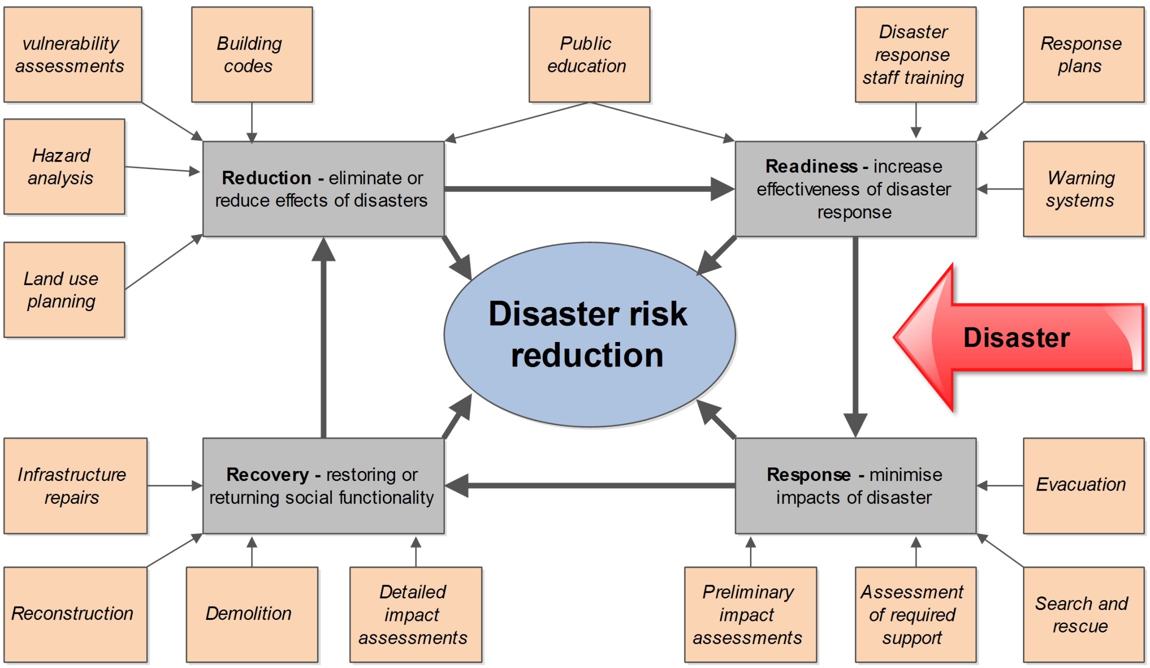


Figure 1.1: Disaster risk reduction framework with common management activities (adapted from Villemure, 2013)

The underpinning framework for disaster risk reduction in New Zealand is the Civil Defence and Emergency Management (CDEM) Framework (Figure 1.2). This framework describes the various disaster risk reduction stakeholders roles and their interactions with one another. A statutory requirement of the Civil Defence Emergency Management Act (2002) is that every CDEM group has a plan which can strengthen relationships between CDEM agencies, allow co-operative planning between various agencies, and nurture effective risk reduction, readiness, response and recovery. One aspect of group plans is to create contingency plans to define roles and responsibilities of key disaster response agencies, and determine likely resource requirements in the event of a disaster (ACDEMG, 2013). Contingency plans are produced by CDEM groups at a local or regional level with input from groups such as lifeline utilities (e.g. Auckland Lifelines Group) and Crown Research Institutes (e.g. GNS Science).

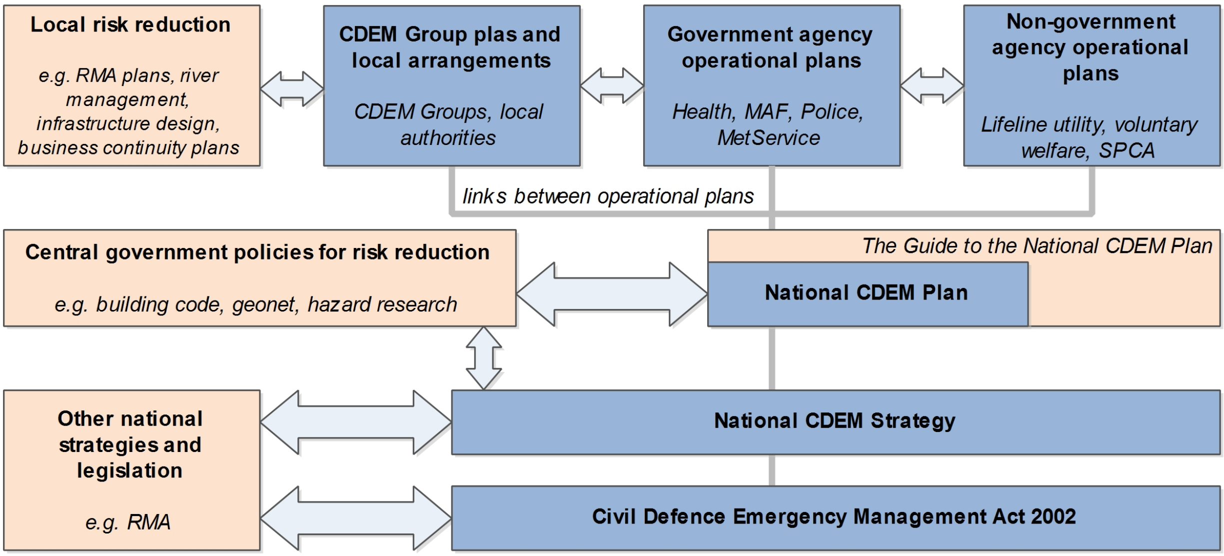


Figure 1.2: New Zealand CDEM Framework (adapted from Department of Internal Affairs, 2008

This thesis focuses on clean-up of tephra (material ejected from volcano during explosive eruptions; Parfitt & Wilson, 2009) after volcanic eruptions. Many existing recommendations for tephra clean-up are based on anecdotal evidence from a few clean-up operations of cities, towns, and airports (e.g. USGS, 2012). This thesis provides the first systematic and robust review of clean-up operations comparing and contrasting different cities and eruption characteristics. It is of critical importance for forming an evidence base for clean-up operation response. This information can then be used to inform modelling of potential impacts, as done in this thesis for Auckland, New Zealand.

Auckland has a population of approximately 1,300,000 (Statistics New Zealand, 2014a) and contributes approximately 35% to New Zealand Gross Domestic Profit (GDP) (Statistics New Zealand, 2014b), but can potentially be impacted by a range of volcanic hazards. This means that understanding potential impacts and the response required to a range of volcanic eruption scenarios for Auckland is an important aspect of disaster risk reduction in New Zealand. Auckland Civil Defence Emergency Management Group (ACDEMG) produced a contingency plan for response to a volcanic eruption within the Auckland Volcanic Field (AVF) in 2013. The contingency plan defines ACDEMG as being responsible for coordinating clean-up and disposal of tephra and also suggests potential tephra disposal sites. However, information such as likely volumes of disaster waste, methods of collection and disposal, costs of clean-up, and clean-up operation duration would also be of use to define potential resource requirements needed.

In the United States, models have been developed to assess potential losses from hurricanes, earthquakes, or floods and commonly include waste volume estimates (FEMA, 2009a,b,c). This is a result of the substantial work done by earthquake and flood engineers over many decades to assess urban vulnerability to these events (Calvi et al. 2006). Comparatively, vulnerability assessments of urban areas to volcanic disasters are still in their infancy, although there have been efforts to quantify volcanic impacts (Blong, 1984; Wilson et al., 2011; Jenkins et al., 2014a; Wilson et al., 2014).

1.2 Aims and objectives

The research objectives of this thesis are as follows:

- Review and analyse tephra clean-up operations to obtain an understanding of the challenges and best approaches for tephra clean-up in Auckland, New Zealand
- Determine relationships between tephra intensity (i.e. thickness or volume) and clean-up metrics such as cost, time, and demand
- Conduct a deterministic impact assessment of the geospatial distribution of tephra fall and pyroclastic flow deposits for clean-up in Auckland under four scenarios
  - Two proximal eruptions
  - Thin tephra fall (1mm) from distal eruption
  - Thick tephra fall (10mm) from distal eruption
- Undertake a geospatial network analysis to determine optimal disposal sites

and to inform clean-up cost and duration estimates for the four outlined scenarios

1.3 Background of Auckland volcanic hazards

Auckland's volcanic landscape - from Rangitoto Island in the Hauraki Gulf, to Lake Pupuke maar crater in the North Shore, to land based scoria cones such as Mt Eden and One Tree Hill - offer some of the most iconic views within the Auckland region. Their formation represents intermittent periods of monogenetic basaltic volcanism over more than 140,000 years. Yet today, these landforms are an important reminder for a risk to New Zealand's economic and social stability: a reawakening of the Auckland Volcanic Field (AVF). The AVF covers an area of approximately 400 km^2 across the Auckland region (Figure 1.3). Eruption styles range from maar crater and tuff ring forming phreatomagmatic eruptions to effusive magmatic eruptions producing scoria cones and lava flows (Edbrooke et al., 2003). Although AVF eruptions are categorised as low-frequency low-magnitude events, the presence of a heavily populated and built-up environment directly on top of the volcanic field means such an event would be high consequence. Considerable effort has been undertaken toward understanding the impacts that a reawakening AVF would have on modern New Zealand through the Determining Volcanic Risk in Auckland (DEVORA) research programme. This programme is tasked with categorising and assessing Auckland volcanic geology, hazard, and risk.

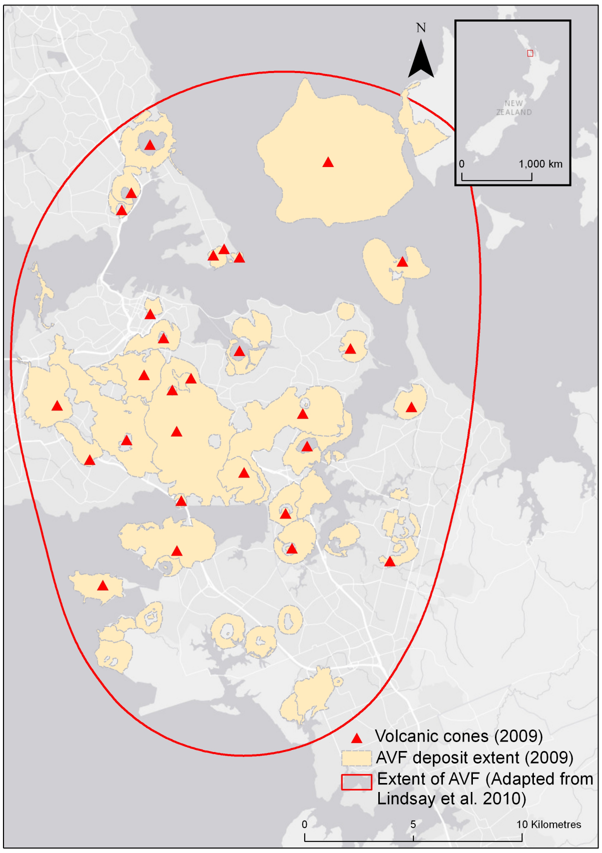


Figure 1.3: Extent of the Auckland Volcanic Field

Identified potential hazards of an AVF eruption include: tephra fall, base surges, explosions, lava flows, edifice building, and earthquakes (Edbrooke et al., 2003). Base surges and lava flows typically heavily impact anything they come into contact with (Wilson et al., 2014), but they are more spatially confined than tephra fall. Tephra fall can impact widely on critical infrastructure (e.g. roads, airports, electricity networks, and waste water systems), buildings, and public health (Wilson et al., 2011; Wilson et al., 2014). Tephra fall sources (Figure 1.4) can come from the AVF, as well as from distal locations including Taupo Volcanic Zone and Mt Taranaki (Edbrooke et al., 2003; Green et al., 2014). Tephra from distal sources is likely to be fine grained and of rhyolite and andesite composition (Moore, 1991; Shane & Hoverd, 2002).

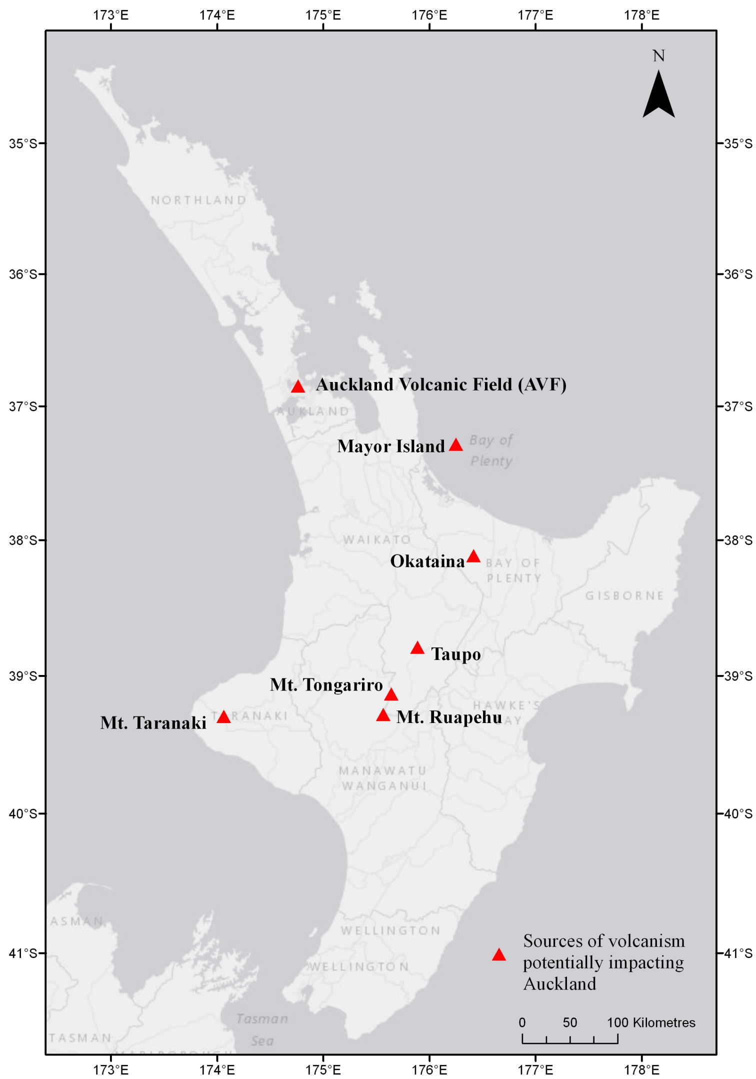


Figure 1.4: Sources of tephra fall with the potential to impact Auckland

1.4 Applying a risk management framework to disaster waste management

Risk management provides a methodical, consistent, and robust assessment towards volcanic risk reduction and has been used extensively for managing volcanic risk to society (Blong, 2000). Assessing the risks volcanoes pose to society can be viewed within a risk management framework (Figure 1.5), which considers three key components: (1) Risk identification, (2) Risk analysis, and (3) Risk evaluation. Although the focus of this thesis is assessing impact, a risk management framework is adopted for assessing clean-up operation impacts to Auckland.

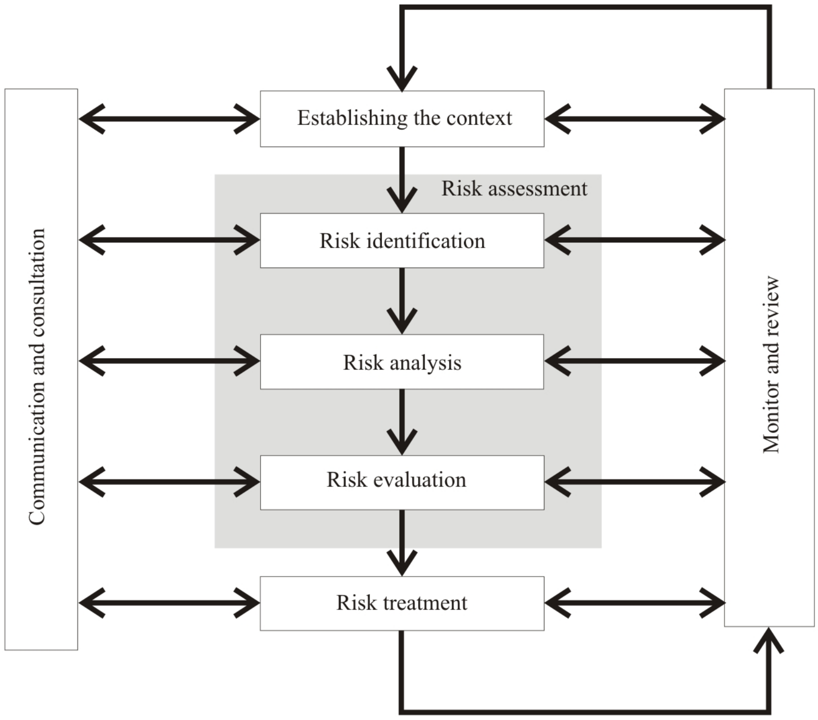


Figure 1.5: Risk management framework (AS/NZS ISO - 31000, 2009)

1.4.1 Risk Identification

Risk identification is recognising the range of hazards which a community is exposed to, and what aspects of society are vulnerable to those hazards (Blong, 2000). Basic aspects of society include: people, buildings, primary production, and infrastructure. However, hazards can also pose a risk to economic, environmental, and cultural values (Sword-Daniels et al., 2014).

Risk identification in the context of disaster waste management requires identifying hazards and characterising how they can impact on the disaster waste management system and societal features which the disaster waste management system relies upon. A step towards risk identification is reviewing past experiences of disaster waste management from around the world. This provides an understanding of challenges associated with disaster waste clean-up, and determine likely future constraints (e.g. data requirements/limitations or legal frameworks). An extensive review of past tephra clean-up operations is provided in Chapter 2.

1.4.2 Risk analysis and evaluation

Risk analysis is about understanding hazards interact with vulnerable components of society. This requires combining hazard assessments (e.g. likely magnitude and frequency of perils) with vulnerability assessments (degree of system to experience harm hue to the hazard). Different volcanic hazards have different impact footprints on society. Generally explosive eruptions will have a larger impact on society than effusive eruptions due to the occurrence of widely dispersed tephra fall and/or highly destructive pyroclastic flows. Although flow hazards (e.g. pyroclastic density currents, lava flows) are much more destructive to the components of society that they come into contact with, tephra fall is most likely to impact on the greatest area, albeit with variable intensity (Wilson et al., 2012). Potential for volcanic hazards to disrupt, damage, or destroy generally decreases with distance from the source of eruption (Wilson et al., 2014). In addition, the probability of a particular magnitude of hazard varies depending on the temporal frame of reference. Generally, this means that high impact events are less likely to occur within a given time frame than low impact events. Applying risk analysis principles within disaster waste management is to geospatially model hazard footprints and the components of society (e.g. roads, buildings, businesses, recreational areas) they impact. This determines the exposure of a range of assets to such impacts.

Risk evaluation weighs different risks to determine what action should be taken for risk reduction. Therefore, understanding what is acceptable, tolerable, and unacceptable risk is critical to disaster waste management. In context of tephra clean-up this means answering the following questions:

- What areas are clean-up priority areas (e.g. roads, residential areas, business areas)?
- What methods of clean-up should be used?
- How much material needs to be removed?
- What resources would be required?
- How much will clean-up cost?
- How long will clean-up operations last?

1.4.3 Monitor and review

Throughout the entire risk assessment process it is important to use up-to-date information. In the late 1990s and early 2000s a series of reports assessing volcanic ash clean-up in Auckland were produced (Table 1.1). Although these reports provided a useful starting point, there has been a substantial number of tephra clean-up case studies collected through volcanic impact reconnaissance missions over the last 15 years which allows for analysis and evaluation to be based upon an improved knowledge base. Additionally, new geospatial data (e.g. building footprints, impervious surfaces, road network) are now available which allows for more sophisticated analysis of Auckland clean-up impacts.

1.5 Research methodology and thesis structure

The body of this thesis is comprised of three chapters which consider different aspects of the risk management process outlined in Figure 1.5 of (1) Identification, (2) analysis, (3) evaluation.

Identification was conducted by undertaking a review of tephra clean-up experiences from literature (Chapter 2). The purpose of the review is to identify common problems and methodologies of managing tephra clean-up in urban environments and to inform volcanic impact assessments. This chapter was co-authored by Dr Thomas Wilson and Dr Christina Magill. Mr Hayes wrote the chapter, analysed data and made all figures. Dr Wilson conceived the development of the chapter, assisted with editing of the chapter, and provided assistance with data analysis. Dr Magill provided data on clean-up operations in Kagoshima, Japan and provided editorial suggestions.

Analysis was conducted by utilising a range of eruption scenarios and assessing the geospatial extent of tephra impact. The purpose of this analysis is to estimate the required volumes of tephra that would need to be collected and disposed of, what methods and resources would be required, how long it would take to clean-up, and how much it would cost (Chapter 3).

Finally, evaluation is conducted by providing a range of recommended planning and future research initiatives which would be of benefit to reduce the impact of having to clean-up Auckland after a volcanic eruption (Chapter 4).

Table 1.1: Previous volcanic eruption clean-up work for Auckland City

Reference	**Research purpose**	**Key outcomes**
Paton et al. (1999)	Model impact of clean-up	- Cost and volume of clean-up
Johnston et al. (2001)	Assess Paton et al.(1999) results in context of collection and disposal issues	- Identified co-ordination and prioritisation needs to be addressed - Suggest that personal protection equipment will need to be provided to clean-up workers - Double handling should be minimised - Maintenance of plant and machinery will be required - Clean-up methods need to be considered in more detail - Tephra needs to be cleaned as quickly as possible, but could take from several weeks to several months - Existing landfills provide insufficient capacity except in the smallest of scenarios - Best disposal sites are quarries and gullies to north and south of Auckland. Multiple locations might be required. - Identified desirable features for disposal locations - Disposal would be covered under Section 330 'Emergency works and power to take preventative or remedial action' - Identified need for more detailed qualitative and quantitative work on impacts of volcanic ash on engineering lifelines
Dolan et al. (2003)	Geospatial analysis to identify potential disposal sites in Auckland	- Identified 16 potential sites suitable for disposal which have since been adopted into the Auckland Volcanic Field Contingency Plan 2013

Chapter 2

Tephra fall clean-up in urban environments

2.1 Introduction

Tephra fall can damage and disrupt critical infrastructure networks, impact buildings (interior contamination, and damage to services and structural components), and affect human health (Table 2.1) (Blong, 1984; Spence et al., 2005; Horwell & Baxter 2006; Wilson et al., 2012; Lombardo et al., 2013; Jenkins et al., 2014a). Furthermore, tephra fall is the most widely dispersed of all the volcanic hazards, often affecting communities hundreds of kilometres away, sometimes for many years due to on-going eruptions or remobilisation of deposits (Wilson et al., 2012). Remobilisation of tephra deposits can be a particular challenge, creating an on-going hazard to exposed communities (Wilson et al., 2011). All of these impacts can lead to knock-on effects such as disruption of social and economic activities (Sword-Daniels et al., 2014). Tephra fall clean-up operations have been widely utilized in urban environments following a tephra fall to reduce impacts. However, such operations can be challenging, time consuming and expensive (Blong, 1984; Wilson et al., 2012).

Tephra fall clean-up operations in urban environments involve the removal of tephra to hasten restoration of social and commercial functions by reducing health, property and infrastructure impacts from in-situ and remobilising tephra. Often this requires tephra to be completely removed to a location where tephra can be immobilised (i.e. disposal sites). Timely, efficient and coordinated tephra clean-up operations have been identified as a crucial aspect of responding to a tephra fall, yet many communities who have experienced tephra falls used trial and error approaches to clean-up due to a lack of pre-event planning. This can increase costs and

Table 2.1: Potential tephra impacts (assuming 1mm tephra thickness) within the urban environment in the absence of clean-up

	Potential Impact	Explanation	Cause of impact	References
Buildings	Structural damage	Roof and structural building component failure	Tephra loads exceeding the strength of roof material and/or support structure	Jenkins et al (2014)
	Non-structural damage	Roof corrosion	Prolonged contact with ash leachates	Oze et al (2014)
		Gutter failure	Tephra loads exceeding gutter strength	Jenkins et al (2014)
		Heating, ventilation, and air-conditioning shut down	Become clogged with tephra	Wilson et al (2012)
	Interior building contamination	Building contents	Ingress of tephra through cavaties.	Wilson et al (2011)
Transport	Driving hazards	Reduced visibility	Tephra fall and remobilisation of tephra deposits	Wilson et al (2012)
		Reduced traction	Tephra deposition on roads	
		Obscured road markings and signage	Tephra deposition on roads and signage	
	Airport closures	Reduced traction on runway	Tephra deposition on runways	Guffanti et al (2009)
Waste water infrastructure	Reduced functionality	Blocked storm water drains	Tephra entering storm water drains	Wilson et al (2012)
	Damage	Abrasion on pipes		
Public health	Physical	Respiratory, eye or skin irritations	Accumulation to ashy environments	Horwell and Baxter (2006)
	Psychosocial	Anxiety, frustration, and depression	Constant reminder of disaster and perception of lack of recovery	Brown et al (2011); Sword-Daniels et al (2014)

reduce efficiency (Blong, 1984; Wilson et al., 2012). Previous studies have identified clean=up operations as challenging to execute due to: uncertainty of the duration, frequency, and spatial distribution of tephra falls; whether tephra remobilises (i.e. by wind); disruption of infrastructure (e.g. transport networks); lack of adequate clean-up resources (e.g. street sweepers and trucks); and identification of disposal sites which met economic, environmental, and social needs (Blong, 1984; Johnston et al., 2001; 2009; Magill et al., 2013; Sword-Daniels et al., 2014). Therefore, planning for tephra clean-up is important for communities to reduce the consequences of tephra fall hazards.

Planning for tephra fall clean-up includes assessing the likely volume of tephra requiring removal, strategies for clean-up and disposal, resource requirements, and estimated costs. However, there are few available studies to inform such planning, largely due to a lack of systematic review of clean-up operations globally and from a range of eruption types. This limits the ability of planners to accurately estimate likely clean up volumes from different tephra types and loadings, which clean up and disposal strategies are most effective, and what resources are required (Blong, 1984; Paton et al., 1999; Magill et al., 2006). This chapter undertakes a systematic review of methods and experiences of tephra fall clean-up in urban environments around the world to create an evidence base for impact assessments and guidance for planning. This chapter contributes to the overall thesis objectives by determining what methods of clean-up should be use in different tephra hazard scenarios and how to assess removal volumes, cost of clean-up, and clean-up duration. It aims to do this by consolidating and analysing the extensive published and unpublished literature on tephra clean-up experiences. This review first assesses the following clean-up metrics for use within impact assessments:

- Collected volumes of tephra
- Duration of clean-up operations
- Clean-up operation costs

Then, a review of tephra collection, disposal stabilisation methodologies, and tephra properties is presented.

2.2 Methods

2.2.1 Catalogue and data sources

I have created a catalogue which records (where available) clean up and disposal strategies for urban environment exposed to tephra fall. This includes: the volume of tephra fall deposited on each urban environment; volume of tephra collected during clean-up; clean-up methods; duration and cost; and methods of disposing tephra (Table 2.2). The catalogue is based on a) published sources including research papers (e.g. Wilson et al 2012), books (e.g. Blong, 1984) and reports (e.g. Casadevall, 1993); and b) unpublished data collected from an international volcanic impacts research group which has undertaken impact assessments in areas affected by volcanic eruptions (e.g. Wilson et al., 2013).

The catalogue distinguishes between communities which have conducted a) clean-up operations in response to a single discrete tephra fall and as a consequence are inexperienced at tephra clean-up; and b) clean-up operations in response to on-going tephra falls, which occur frequently over a period >6 months allowing the community to gain experience managing tephra fall clean-up. This distinction is necessary as a community's tolerance and capacity to manage tephra falls may differ in different social contexts and/or change with more frequent tephra falls (Sword-Daniels et al., 2014). For instance, Kagoshima city in Japan has experienced regular tephra falls from Sakurajima volcano since the 1950s (Japan Meteorological Agency, 2013) and has become experienced and adapted to deal with tephra clean-up operations (Durand et al., 2001).

Table 2.2: Data sources

Eruption	Locality	Data	References
Volcan Irazu (1963-1965)	San Jose, Costa Rica	Methods	Clark & Lee (1965)
Eldfell (1973)	Heimaey, Iceland	Accumulation	Self et al. (1974)
		Collection	Williams & Moore (1983); Morgan (2000)
		Methods	
		Disposal	
Mt. St. Helens (1980)	Yakima, USA	Accumulation	Sneva et al. (1982)
		Collection	Blong (1984); Zais (2001)
		Duration	
		Disposal	
	Ritzville, USA	Accumulation	Mclucas (1980)
		Collection	Blong (1984)
		Methods	
	Portland, USA	Accumulation	Blong (1984)
		Collection	
		Duration	
		Methods	
	Moses Lake, USA	Accumulation	Blong (1984)
		Collection[1]	
	Grant county airport, USA	Accumulation	Casadevall (1993)
		Collection	
		Disposal	
	Grant County roads, USA	Disposal	Blong (1984)
	Spokane International Airport, USA	Accumulation	Schuster (1981)
		Collection	Casadevall (1993)
	Spokane County, USA	Disposal	Blong (1984)
	Adams County, USA	Disposal	McLucus (1980)
Mt. Hudson (1991)	Chile Chico	Accumulation	Naranjo et al.(1993)
		Collection[2]	Wilson et al. (2009)

[1]Estimated from disposal piles
[2]Unsure of data quality

		Duration	Wilson et al. (2009)
		Methods	Wilson et al. (2009)
		Disposal	Wilson et al. (2009); Wilson et al. (2011)
	Los Antiguos	Accumulation	Naranjo et al. (1993)
		Collection[3]	Wilson et al. (2011)
		Duration	Wilson et al. (2009)
		Methods	Wilson et al. (2009); Wilson et al. (2011)
		Disposal	
	Perito Moreno	Disposal	Wilson et al. (2011)
Mt Pinatubo (1991)	Cubi Point Naval Base, Phillipines	Accumulation	Casadevall (1993)
		Collection[4]	
		Methods	
Mt. Spurr (1992)	Anchorage, USA	Duration	Johnston (1997)
		Methods	
		Disposal	
Mt Etna (2002)	Catania, Italy	Collection	Barnard (2004)
		Methods	
		Disposal	
Reventardo (2002)	Quito	Methods	Leonard et al. (2005)
		Disposal	
Chaiten (2008)	Futaleufu	Accumulation	T.M. Wilson unpublished field notes
		Collection	
		Duration	
		Disposal	
Redoubt (2009)	Anchorage, USA	Accumulation	Wallace et al. (2013)
		Methods	T.M. Wilson unpublished field notes
Pacaya (2010)	Guatemala City, Guatemala	Accumulation	Wardman et al. (2011)
		Collection	
		Duration	
		Methods	
Puyehue-Cordn Caulle	Bariloche, Argentina	Accumulation	T.M. Wilson unpublished field notes

[3]Unsure of data quality
[4]Estimated from 25,000 dump truck loads carrying 6 m^3 per truck

(PCC) (2011)		Collection[5]	
		Duration	Wilson et al. (2013)
		Methods	
		Disposal	
	Villa la Angostura, Argentina	Accumulation	T.M. Wilson unpublished field notes
		Collection[6]	
		Methods	Wilson et al (2013)
		Disposal	
	Jacobacci, Argentina	Disposal	Wilson et al. (2013)
Shinmoedake (2011)	Miyakonojo, Japan	Accumulation[7]	AIST, Geological Survey of Japan
	Miyakonojo, Japan	Collection	Magill et al. (2013); T.M. Wilson & C Magill unpublished field notes
	Miyakonojo, Japan	Methods	
	Miyakonojo, Takaharu, Takasake	Disposal	
Sakurajima (1955-present)	Kagoshima, Japan	Accumulation	Kagoshima City (2013)
		Collection	
		Cost	
		Methods	Durand et al. (2001); Ishimine et al. (2012)
		Disposal	
Tongariro (2012)	Central North Island State Highways, New Zealand	Methods	G. Wilson, unpublished field notes
		Disposal	

2.2.2 Quantifying tephra accumulation

Tephra accumulation is used within this review as one of the measures of tephra fall hazard. I define tephra accumulation here as m^3/km^2. I chose this measure over volume as I will be assessing communities of variable spatial extent (cities such as Portland and Yogyakarta, and towns such as Moses Lake). The spatial distribution of tephra impacts influences how tephra clean-up operations are conducted because areas need to be prioritised for clean-up and resources (loaders, trucks, workforce) appropriately distributed. Additionally, the requirement of different types of clean-

[5] Estimated by 250,000 dump truck loads carrying 6 m^3 per truck
[6] Estimated by 950 dump truck loads carrying 10 m^3 per truck
[7] Calculated from overall tonnages

up machinery (graders, loaders, dump trucks, street sweepers) will vary depending on the severity of tephra hazard. Therefore, the volume of tephra per unit area deposited on an urban environment (tephra accumulation) is important in determining the scale and method of clean-up operation required. The following methodology was followed for determining tephra accumulation:

- The urban area subject to tephra deposition, tephra thickness/load, and total volume values were obtained from published isopach maps, literature, and geospatial analysis (Table 2.2).
- Tephra accumulation (m^3/km^2) was determined from Equation 2.1

$$A = \frac{T \cdot UA_1(or volume)}{UA_2} \tag{2.1}$$

Where:
A = Tephra accumulation (m^3/km^2)
T = Tephra thickness (m)
UA_1 = Urban area impacted by tephra fall (m^2)
UA_2 = Urban area (km^2)

2.2.3 Ongoing tephra fall clean-up data Kagoshima, Japan

Due to data availability, methods for assessing tephra clean-up in Kagoshima was adjusted to consider annual averages of tephra accumulation and removal. Available data detailing annual tephra fall load (g/m^2) was recorded at 22 observation points around the city (Kagoshima City, 2013). Using this data, an average annual g/m^2 was calculated for the city area. The dry density of tephra layers on Mount Sakurajima at 3.8 km from Minamidake crater ranged from 1.2 g/cm^2 to 1.4 g/cm^2 between 1972 and 2008 (Teramoto & Shimokawa 2011), and so I have assumed a bulk density of 1.3 g/cm^2. Using this density, average annual g/cm^2 was converted to an annual volume of tephra (m^3). annual tephra accumulation was calculated (Equation 2.1) assuming tephra impact on the urban area of 547 km^2 (urban area of Kagoshima).

2.3 Tephra clean-up metrics for impact assessments

2.3.1 Volume removed

International case studies, including both discrete and ongoing tephra falls, indicate that as tephra accumulation decreases, so too does the proportion of tephra that is collected (Figure 2.1). There is some variability in this trend, which can be explained by varying levels of data quality (See footnotes Table 2.2). Additionally, estimates for Yogyakarta (Kelud 2014) appear low although tephra could still be observed in Yogyakarta 6 months after the eruption. Regardless, the volume of tephra that is removed is generally low compared to tephra accumulation. Trace falls of tephra (<1,000 m^3/km^2) may require no coordinated clean-up operation, such as in Anchorage following the 2009 Redoubt eruption (T.M Wilson unpublished field notes). An increasingly higher proportion of deposited tephra tends to be removed as tephra accumulation increases, as buildings and other areas beyond roads require cleaning. At tephra accumulations of around or greater than 100,000 m^3/km^2 more than 50% of tephra is removed such as at Heimaey, Iceland (1,920,000 m^3/km^2), or Chile Chico, Argentina (100,000 m^3/km^2), which both required large coordinated efforts towards tephra removal in order to restore functionality to communities.

2.3.2 Clean-up operation duration

Clean-up operations can be disruptive, requiring road closures, coordinated building cleaning and parking restrictions while clean-up crews remove tephra. In Yakima, some 70 mm (70,000 m^3/km^2) of tephra fell on the city following Mt. St. Helens eruption in 1980, causing the central business district to be closed to non-essential personnel for 3 days for clean-up (Blong, 1984). Therefore, the duration of a clean-up operation is an important planning and impact assessment consideration. There is limited information available for clean-up duration, but the available data indicates large variability (Figure 2.2). Supporting qualitative descriptions indicate in some situations clean-up duration is prolonged as a result of sporadic and recurring tephra falls. An estimated 45,000 m^3 (50,000 m^3/km^2) of tephra fell on Futaleufu, Chile after the 2008 eruption of Chaiten; this took around 9 months to clean-up and intermittent tephra fall and remobilisation required occasional clean-up for a further 6 months. However, ongoing tephra fall is not always the reason for prolonged clean-up. Clean-up of Portland following an eruption of Mt St. Helens lasted 10 weeks even though tephra accumulation was only 1,500 m^3/km^2 (825,000 m^3) and less

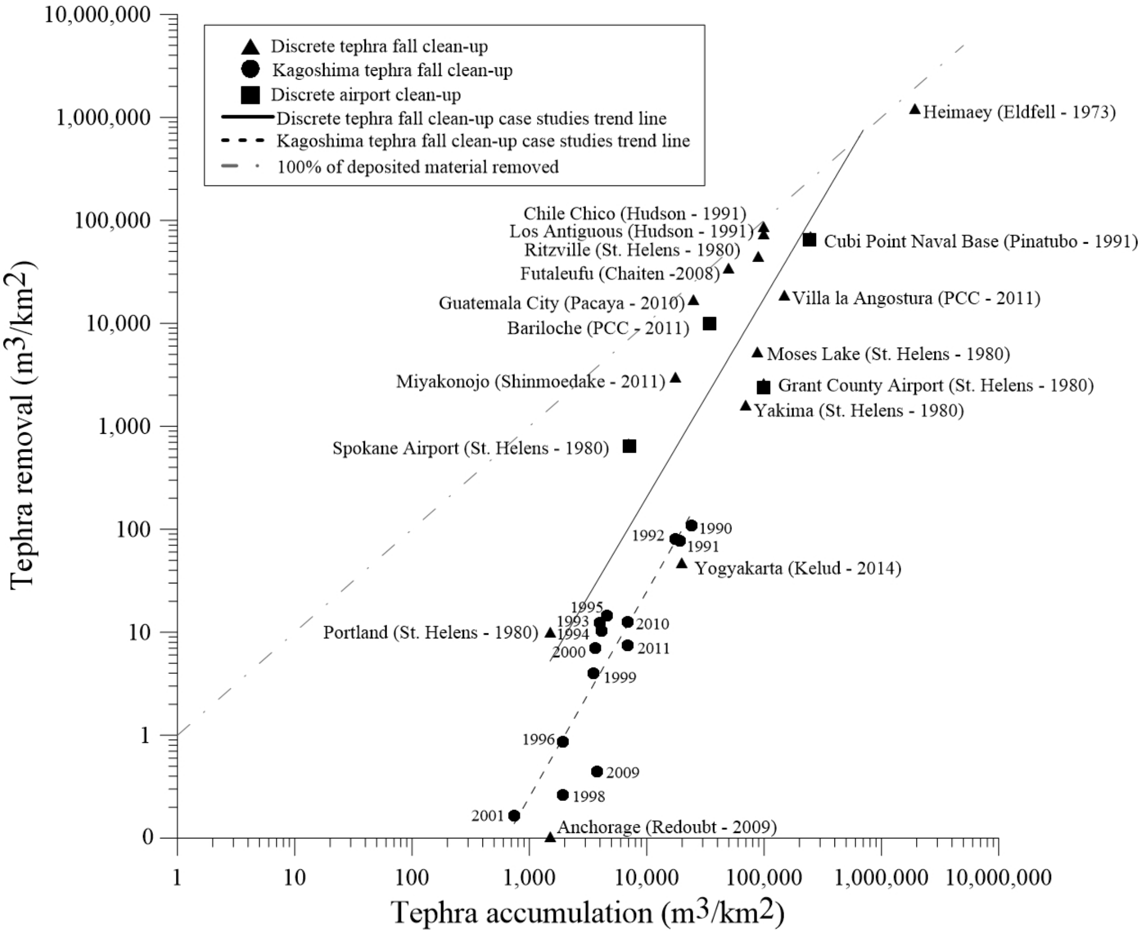


Figure 2.1: Tephra fall accumulation and the amount of tephra collected. Dotted line indicates 100% tephra collection. Discrete tephra collection $R^2 = 0.76$, Kagoshima tephra collection $R^2 = 0.82$

than 1% (5400 m^3) was removed. The long duration was attributed to the very fine grain size (median grain size 31 µm; Shulters & Clifton, 1981) of the tephra deposited on the city which reduced the performance of street sweepers (Blong, 1984). In comparison, Yakima had 70,000 m^3/km^2 (4,900,000 m^3) of coarser tephra fall (median grain size 125 µm; Carey & Sigurdsson 1982), and it only took seven days (twenty four hours per day operation) to remove (109,000 m^3) (Blong, 1984).

2.3.3 Tephra clean-up and removal costs

Tephra clean-up operations can be expensive undertakings due to extensive areas requiring cleaning and large volumes of tephra requiring removal. For example, clean-up costs in Bariloche, Argentina (PCC 2011) were reported at US$35 million (Wilson et al., 2013). However, it can be difficult to determine the true cost of clean-up because often only direct costs such as machinery hire or transportation and dumping costs are reported (Blong, 1984). Indirect costs, such as business dis-

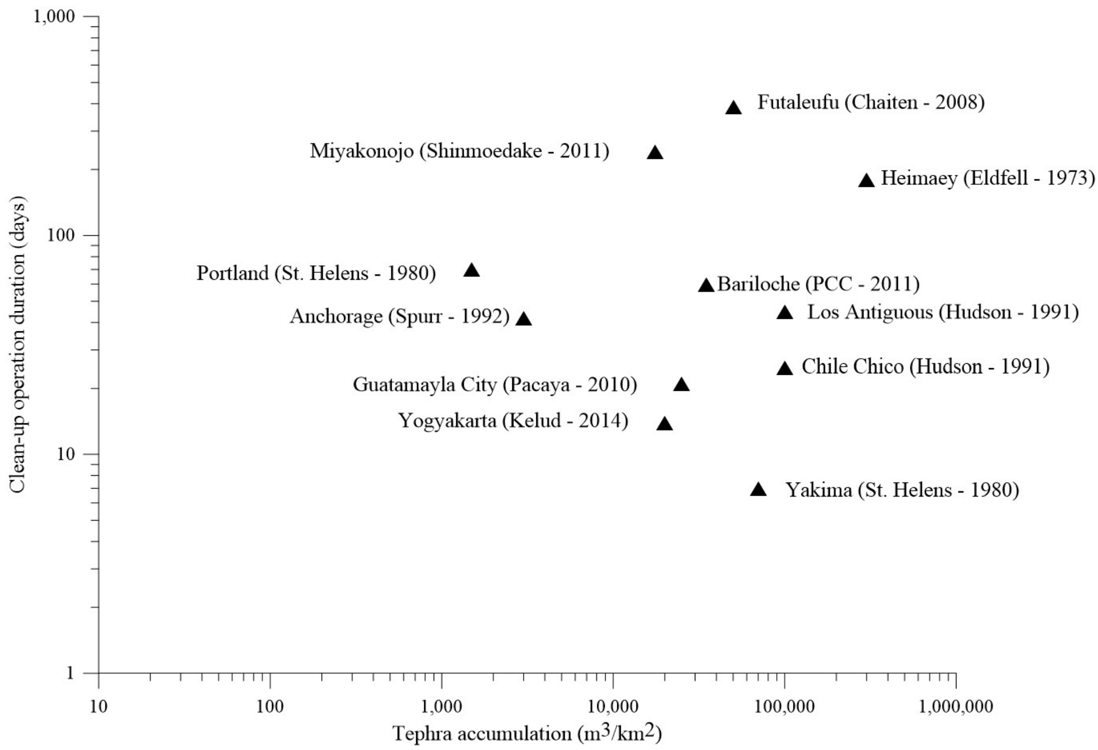


Figure 2.2: Tephra accumulation and the duration of clean-up operation. Futaleufu clean-up duration here is the duration of primary clean-up operation. Note: Cleanup duration converted to days from estimates (e.g. about a month) assuming 30 days to a month. Where time ranges were given the middle value is used (e.g. cleanup took 1-2 months = 45 days).

ruption, can also occur because of closures to areas while clean-up is conducted. Analysis of clean-up costs undertaken in the following sections only considers direct costs of clean-up and particular focus has been given to Kagoshima due to data availability. It is important to consider that Kagoshimas clean-up costs are aggregated annually, therefore direct comparisons between tephra removal costs in Kagoshima and discrete tephra fall communities are not possible.

2.3.3.1 Tephra clean-up and removal costs - road length

Roads are cleaned in every instance where coordinated clean-up operations have been initiated. Therefore, analysis of how clean-up costs change depending on the length of roads requiring tephra removal could be useful for impact assessments (Figure 2.3). Discrete tephra fall communities do not appear to follow any statistically significant relationship. A reason for variability between discrete tephra fall communities is that it is not possible to distinguish between different road characteristics (e.g. road type and road surface). This distinction is important because these characteristics will influence the thoroughness of road cleaning required and the relative ease with which it can be undertaken. Roads that are high use or located in areas of high human occupation require a greater level of cleaning than low use roads. Additionally, asphalt and gravel surfaces are likely to be of varying levels of difficulty to clean-up, and will influence removal costs. For example, Grant, Spokane, and Whitman Counties in the United States found when removing tephra after Mt. St. Helens 1980 eruptions gravel was also removed in the process (McLucas 1980); this increased volume removal, as well as operation duration as new gravel had to be placed. Unpaved roads also presented a challenge for clean-up in Futaleufu (Chaiten 2008) because when tephra was wet it penetrated down into the roads, but dry it was easily remobilised (T.M. Wilson Unpublished field notes). The solution was to completely dig up and replace the unpaved roads.

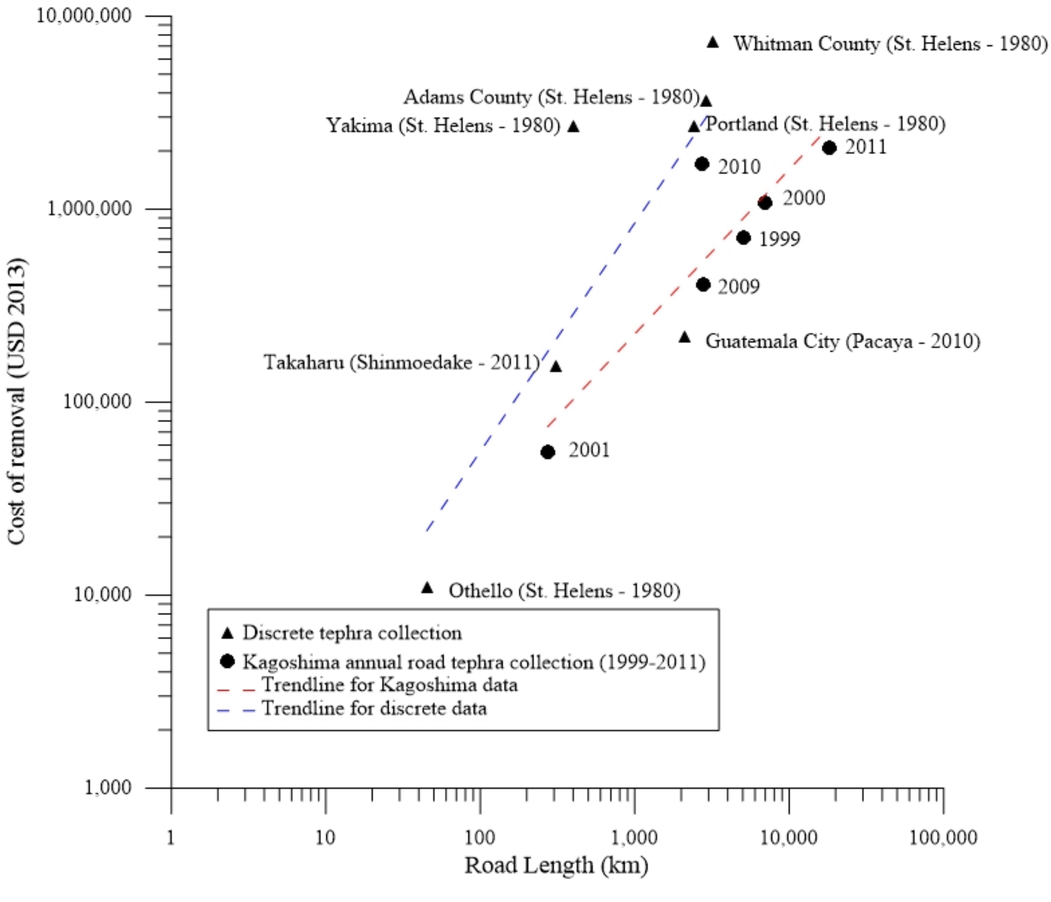


Figure 2.3: Total cost of clean-up compared to length of road requiring cleaning, Yakima, Othello, Adams County data from McLucus (1980); Portland data from Blong (1984). No Kagoshima clean-up 2002-2008. Kagoshima R^2=0.81, discrete R^2=0.63

Kagoshima road clean-up data show a good association between annual length of road that required cleaning and cost of clean-up. This is interpreted to be because similar road types (arterial, highway, rural) and surfaces (asphalt, gravel) are impacted in each event. Due to this data showing averaged clean-up over the entire year, simply increasing the amount of road that was cleaned would also increase the cost of clean-up.

2.3.3.2 Tephra clean-up and removal costs - total volume removed

Clean-up costs are likely to increase in a given community as the volume of tephra to be removed increases because greater numbers of required clean-up machinery and workforce. Disposal costs can also increase if additional disposal sites are required to be established due to volumes of tephra requiring removal. Two data sets of Kagoshima tephra removal were available for analysis: (1) data from 1990-1998 detailing the volume and cost of tephra removal from just residential areas, and (2) data from 1999-2011, detailing volume and removal costs from both residential and road areas. Both data sets show a strong relationship between volume removed and removal cost (Figure 2.4). Residential costs account for most of the clean-up costs for Kagoshima, and a large component of this is from manufacturing and distributing large quantities of bags for residential tephra collection. Close to six million bags were distributed for clean-up between 2010 and 2011 (Kagoshima City, 2013).

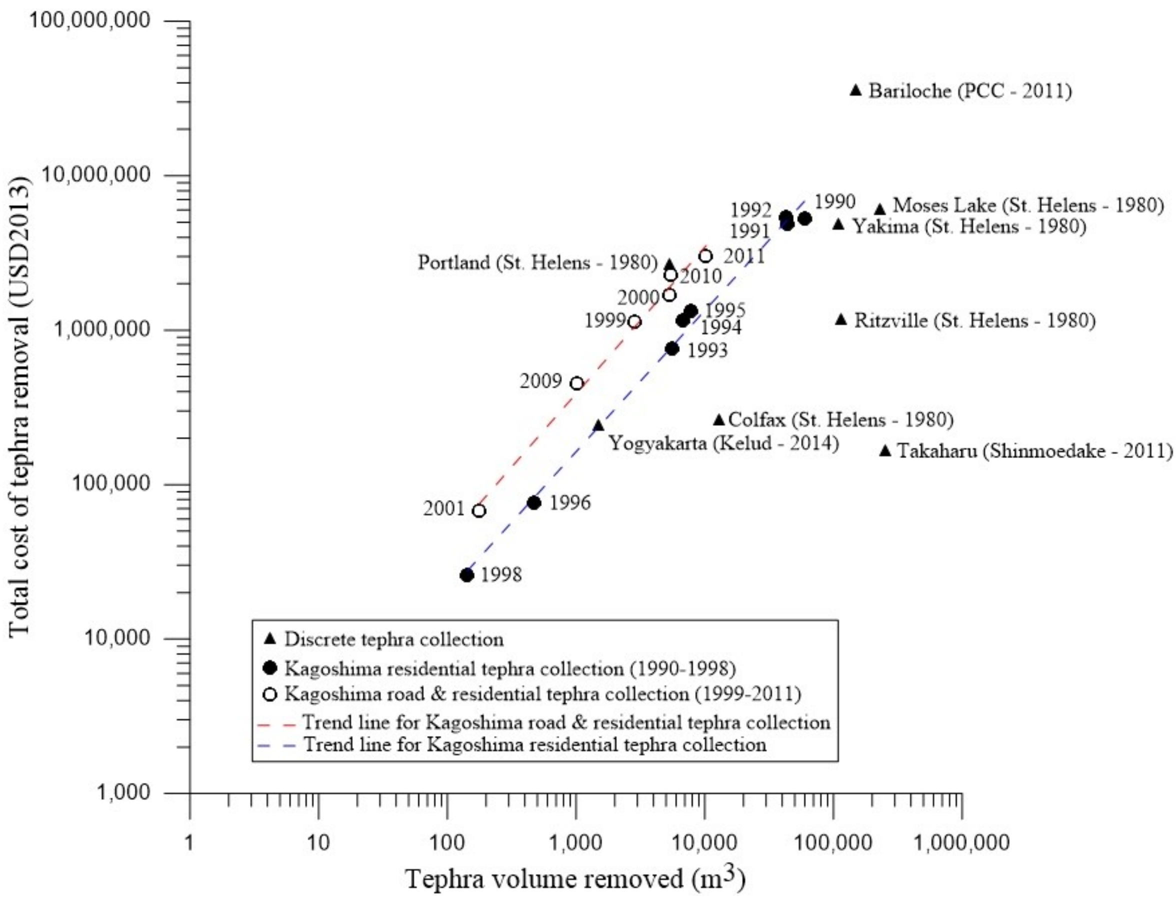


Figure 2.4: Comparing the volume of tephra removed and cost estimates. Note Takaharu data point considers only tephra collected by individuals and does not include road and agricultural facilities clean-up. Both kagoshima relationships $R^2 = 0.99$

Clean-up costs for discrete tephra fall clean-up are also shown in Figure 2.4. However, the relationship between clean-up costs is much weaker than for Kagoshima. This could be because of differing resource availability, methods of clean-up, operation duration, and distance to disposal sites. Transport of material makes up a large part of clean-up operation cost and so where disposal sites are situated could have a big impact on the total cost of clean-up.

2.4 Tephra clean-up methods and management

2.4.1 Urban tephra collection

A catalogue of clean-up methodologies is presented in Table 2.3. There is a broad range of clean-up methods used by the communities reviewed, and no clear tephra accumulation thresholds dictating methods and processes of clean-up have been found. This is due to a broad range of local contextual influences such as: available resources (e.g. dump trucks, graders, and sweeper trucks), land-use, climate, and tolerance for remobilised tephra. However, a common process can be drawn from case studies (Figure 2.5) which indicate three sequential phases: (1) pre-collection, (2) collection, and (3) disposal. Each phase will be outlined in the subsections below.

Table 2.3: Summary of reported collection processes and methodologies (sorted by Accumulation). Shaded cell indicates that activity was reported to have occurred.

Location	Reported Clean-up duration	Thickness of in situ deposit (mm)	Accumulation (m^3/km^2)	Clean-up operation start point	Pre-collection		Residential collection		Urban collection			
					Roof clean	Stabilize tephra	Curb side	Bagged	Graders	Manual	Sweepers	Vacuum
Kagoshima (Sakurajima – ongoing)	Goal of 3 days	Varies (1-5mm)	-	Immediate	■	■		■		■	■	
State Highways (Mt. Tongariro – 2011)	5-13 days	1	-	Immediate		■					■	
San Jose (Irazu – 1963-1965)	Not reported	~5	-	Not reported	■	■	■		■	■	■	■
Portland (St. Helens – 1980)	10 weeks	1-5	$1.5x10^3$	Immediate	■	■					■	
Catania (Mt. Etna – 2002)	Not reported	1.6	$1.6x10^3$	Delayed	■	■		■	■		■	■
Anchorage (Spurr – 1992)	6 weeks	3	$3x10^3$	Day after eruption	■	■		■	■		■	■
Pullman (St. Helens – 1980)	Not reported	12	$1.3x10^4$	Not reported		■	■		■	■		
Spokane City (St. Helens – 1980)	Not reported	13-19	$1.6x10^4$	Not reported		■		■	■		■	■
Miyakonojo (Shinmoedake – 2011)	Feb-Sept 2011	5-30	$1.75x10^4$	Not reported	■	■	■	■			■	
Yogyakarta (Kelud – 2014)	2 weeks	20	$2x10^4$	1 day after eruption	■	■		■		■		
Guatamayla City (Pacaya – 2010)	3 weeks	20-30	$2.5x10^4$	Immediate	■			■		■	■	
Bariloche (PCC -2011)	2 months	35	$3.5x10^4$	Not reported			■		■	■		
Jacobacci (PCC – 2011)	Not reported	50	$5.0x10^4$	Delayed 1 week	■			■	■	■		
Yakima (St. Helens – 1980)	7 days (24hr)	50-80	$7x10^4$	Immediate	■	■	■		■	■	■	■
Ritzville (St. Helens – 1980)	Not reported	80-100	$9x10^4$	Two days after					■	■		
Chile Chico (Hudson – 1991)	Not reported	100	$1x10^5$	Not reported	■	■	■			■		
Los Antiguos (Hudson – 1991)	1-2months	100	$1x10^5$	Not reported	■	■	■		■	■		
Quito (Reventado – 2002)	Not reported	2-5	$2.34x10^5$	Not reported	■	■		■		■		
Cubi Point Naval Base (Pinatubo – 1991)	Not reported	150-200	$2.5x10^5$	Not reported	■	■			■	■	■	
Villa la Angustra (PCC – 2011)	Not reported	150	$2.86x10^5$	Not reported			■		■			
Heimaey (Eldfell – 1973)	April-October 1973	6-2000	$2.5x10^6$	Delayed	■	■			■	■		

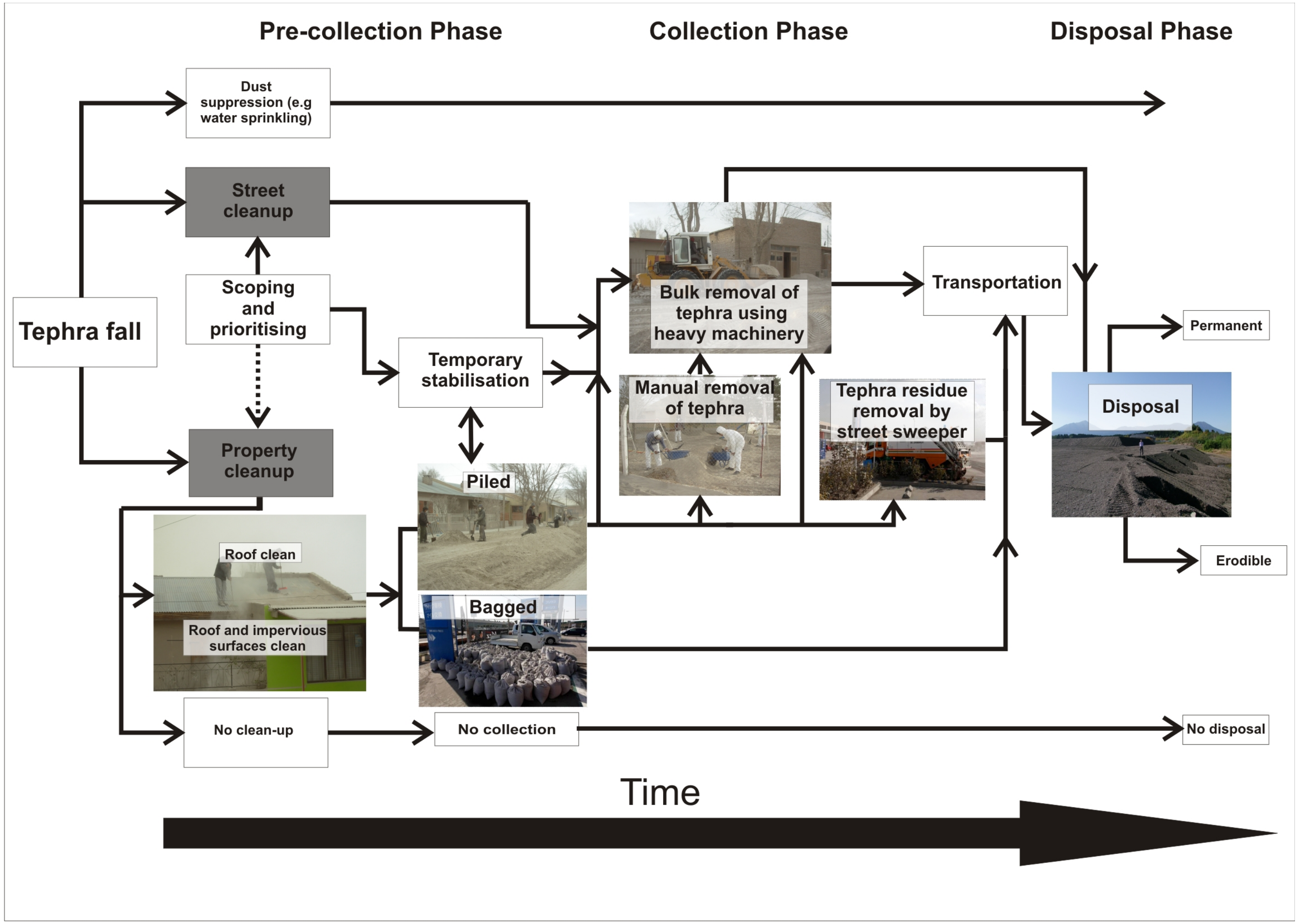


Figure 2.5: Conceptual tephra clean-up process. Photo credits: Jose Mallado and Christina Magill

2.4.2 Pre-collection phase

The pre-collection phase involves planning a coordinated clean-up response as well as preparing the urban environment for clean-up. If pre-event plans were already in place, clean-up can begin relatively quickly following tephra fall because lines of communication between relevant authorities are established. In Guatemala City (Pacaya 2010), clean-up plans were compiled after consideration of the response to the Haiti 2009 earthquake, and were credited with speeding up tephra clean-up (Wardman et al., 2011). One of the first decisions clean-up officials will have to make is when to begin clean-up. Following the 2002 eruption of Mt. Etna, authorities were hesitant to start clean-up due to uncertainty regarding how long the eruption would continue and an unwillingness to pay overtime to clean-up workers for repeated clean-up operations (Barnard, 2004). In Jacobacci after the 2011 Puyehue-Cordn Caulle (PCC) eruption visibility was so poor that clean-up could only start one week later (Wilson et al., 2013). The clean-up of Heimaey following the 1973 Eldfell eruption was delayed approximately 2 months (Morgan, 2000), although was due to the large scale evacuation which occurred on the island.

When cleaning buildings and properties, roofs are completed before removing tephra at ground level to reduce cleaning surfaces multiple times. This requires coordination within the community, and has been a source of conflict when some property owners have not cleaned their roofs within specified time frames (Blong, 1984). Difficulty organising community clean-up can arise where absentee ownership (e.g. rented or empty property) is high (Kartez et al., 1980).

Two methods of property tephra collection are typically used: (1) property owners pile tephra up in designated locations (often 1-2m from curb side) (Figure 2.6a), or (2) tephra is bagged before collection (Figure2.6b). Property clean-up in Kagoshima is conducted by property owners bagging tephra and leaving it at one of the 6,400 collection points around the city (Ishimine et al., 2012). In situations where tephra fall accumulation is low (1,000 m^3/km^2) property owners can dispose of tephra themselves (e.g. in gardens). However, there has been confusion between property owners and clean-up officials about how tephra will be collected. In Anchorage (Spurr 1992), incorrect information given to residents resulted in tephra being disposed of with normal household waste resulting in damage to garbage trucks (Johnston, 1997).

Resources used for tephra removal include heavy earth moving machinery (e.g. loaders and graders), street sweepers and trucks. Vehicles can break down tephra particles into finer grain sizes, which become suspended in the air, and make collection difficult (Blong, 1984). Temporary stabilisation might be necessary depending on the grain size of the tephra deposit. Moistening tephra (1-5 wt.%; Paton et al., 1999; Blong, 1984) is an effective and efficient method. However, water shortages often follow volcanic eruptions (Wilson et al. 2012). In these situations water may not be able to be used to moisten tephra. Additionally, too much water added to the tephra may result in tephra becoming saturated, which when dried becomes cemented to surfaces and difficult to pick up (Casadevall, 1993). Alternative methods have included using wet sawdust as tephra remobilisation suppression (Blong, 1984).

2.4.3 Collection phase

The collection phase involves removal of tephra from surfaces (e.g roofs, roads, paved areas). Some surfaces have a higher priority to municipal authorities for clean-up than others, such as roads in central business districts compared to grass within rural areas. Kartez et al. (1980) interviewed a number of jurisdictions affected by the Mt. St. Helens eruptions and found that downtown business districts and arterial roads were considered the highest priority for cleaning, followed by: hospital areas, public buildings, high density residential areas, and neighbourhood roads. Kagoshima prioritises clean-up by having predefined zones which are assessed for severity of impacts following a tephra fall by officials within the Road Maintenance Division (Ishinmine et al., 2012). The initial focus of clean-up in Bariloche (PCC 2011), which had around 40 mm (35,000 m^3/km^2) of tephra fall, was in high tourism areas such as downtown business streets (Wilson et al. 2013). Clean-up priorities can also be based on resource availability. For example, clean-up priorities in Moscow, Washington (St. Helens 1980) were based on maximising volunteer labour because public resources were very limited. This involved zoning neighbourhoods in 6 zones, each with access to one front-end-loader and a dump truck. When a street had finished piling up tephra at the curb side the loader and dump truck were requested.

Caveats to utilising volunteer workforce are inexperienced operation of resources, and health and safety regulations. Large workforces (e.g. volunteers) required in high accumulation tephra fall events highlights an additional challenge for clean-up management due to health and safety considerations (Wilson et al., 2012). Large numbers of injuries which occur as a result of tephra fall are related to clean-up activities (e.g. falling from roofs) (Leonard et al., 2009; Wardman et al., 2012; Magill et al., 2013). Clean-up activities in Miyakonojo and Takaharu (Shinmoedake 2011) resulted in 36 injuries related to falls from slips or falls from ladders or roofs (Magill et al., 2013). Further, health and safety equipment, such as dust masks and overalls, must be provided to individuals conducting clean-up operations.

In Cheney 10 fire hydrants were damaged by incorrect usage, and over 1,200 metres of fire hose was destroyed due to abrasion by tephra; this raised concerns about the capabilities of fighting a major fire (Kartez et al., 1980). Impacts to surfaces being cleaned has also been observed. The runway at Guatemala International Airport (Pacaya 2010) was badly damaged due to high mechanical strength and abrasiveness of tephra and required resurfacing after tephra removal operations (Wardman et al., 2012).

Typical resources used in order to conduct city street clean-up are heavy earthmoving machinery, dump trucks, street sweepers, and manual labour. Although, no specific thresholds have been found which dictate the methods of clean-up, generally areas which experience thick tephra deposits (>1 cm) will require graders and loaders to first remove the bulk of the tephra (Figure 2.6c), before street sweepers are used to clean up the tephra residue (Figure 6d). Areas affected by thin tephra deposits (<1 cm) usually implement an intensive street sweeping program until particulate levels return to acceptable levels. However, street sweepers in Portland, following an eruption of Mt. St. Helens in 1980, were reported to being only 50% effective at picking up these fine grain sizes (Blong, 1984). This required multiple sweeper runs, and prolonged clean-up operations in the city (Blong, 1984).

Manual cleaning (using brooms and shovels) is resource intensive and time consuming, but is important for areas that are difficult for machinery to reach such as properties (driveways and roofs) or small roads (Figure 2.6e). This was of particular importance in the clean-up of San Jose, where over 20,000 m^3 of tephra was deposited on the city following the eruption of Volcn Iraz in the 1960s when street sweepers could operate in only 40% of the streets, which meant the rest had to be cleaned manually (Clark & Lee, 1965). In Takaharu (Shinmoedake 2011), which experienced 2-20 mm of tephra fall, 4 house roofs could be cleaned by a team of 5 people each day (Magill et al., 2013).

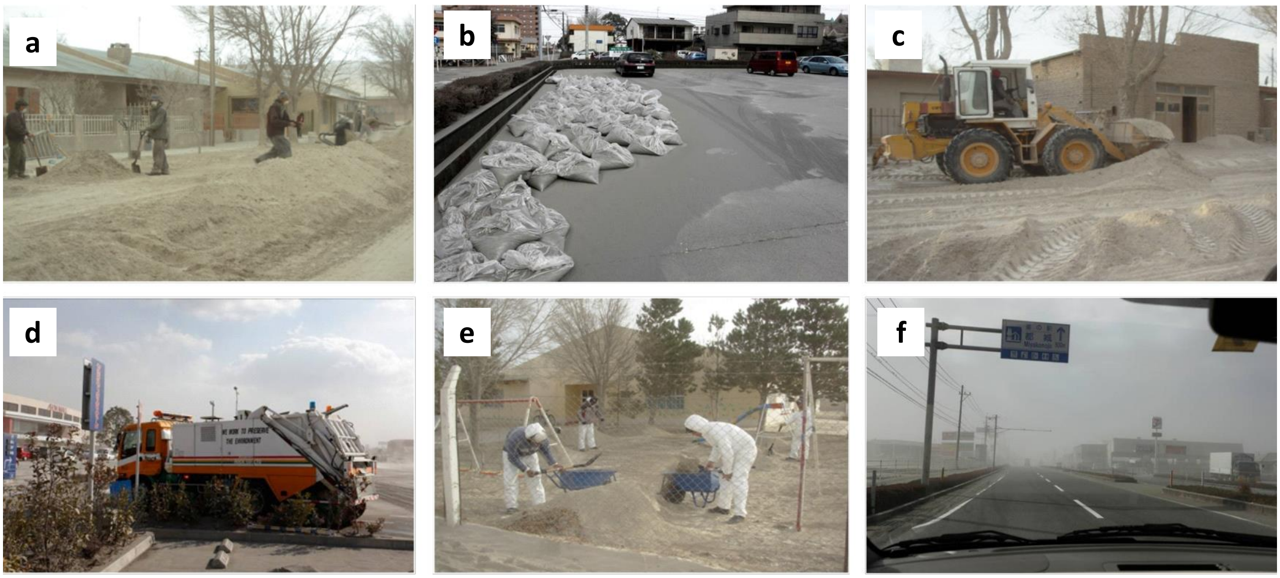


Figure 2.6: a) Manually piling tephra in street for heavy machinery to remove in Jacobbacci Argentina (PCC 2011) (Photo credit: Aileen Rodriguez), b) Bagged tephra in Miyakonojo City Centre, Japan (Shinmoedake 2011) (Photo credit: Christina Magill), c) Heavy machinery removing tephra in Jacobacci, Argentina (Photo credit: Aileen Rodriguez), d) Street sweeper in Miyakonojo City Centre, Japan (Photo credit: Christina Magill), e) Manual cleaning in Jacobacci, Argentina (Photo credit: Aileen Rodriguez), f) Airborne remobilisation of fine grained volcanic ash in Miyakonojo City Centre, note recently cleaned road (Photo credit: Christina Magill)

2.4.4 Disposal and permanent stabilisation

A wide range of disposal methods have been implemented across case studies (Table 2.4). Existing waste disposal sites have been used when tephra volumes are low enough to be feasible. However, disposal of large volumes of tephra can put pressure on, or exceed, the capacity of existing waste disposal operations greatly reducing the design life. Therefore, using existing waste disposal systems is not always appropriate. One of the most common alternative methods is to fill in open spaces such as abandoned quarries, valleys, or fields. In Villa la Angostura (PCC 2011), 95,000 m^3 of tephra required disposal. Initially, provisional disposal sites were located in each neighbourhood. Eventually, tephra and small amounts of lahar deposits were used to fill in an old quarry which had become a lake (Figure 2.7a-f). Uses for tephra other than as landfill have also been utilized. In Miyakonojo (Shinmoedake 2011), sand bags were filled with tephra for flood protection. Following the 1992 Spurr eruption, authorities in Anchorage used tephra as road grit by placing it on top of icy roads. Additionally, pyroclastic material (fall and flow) of coarse sand grain size is used heavily for construction material in Indonesia and mining of these materials from areas near volcanoes has become widespread (De Blizal et al., 2011).

Once a disposal site is established, stabilisation of the tephra at the disposal site is often undertaken (Table 2.5). The purpose of stabilisation is to prevent tephra remobilisation over the long term. Methods of stabilisation have to consider the environmental standards of the community. The most common form of stabilisation is capping deposits with soil and planting vegetation which helps bind tephra together (Wilson et al., 2011). This method was used for tephra stabilisation from the 2008-09 eruption of Chaiten, Chile. Photos of the disposal site taken in 2009 and 2012 show the change in site appearane as vegetation has become established (Figure 2.8).

Occasionally, no permanent stabilisation is undertaken and the tephra deposit is allowed to be erode naturally. For example, clean-up of State Highways 1 and 46 following the Te Maari (Tongariro) eruption in 2012 only involved moving tephra to the side of the roads and left to naturally erode. In this instance, the amount of tephra deposited was low enough (1 mm) and in an area of relatively low human occupation that tephra volume was not sufficient to cause serious impacts. However, if no stabilisation efforts are taken to prevent remobilisation following heavier falls or areas of high human occupation, tephra can create a hazard to communities. No stabilization was conducted at the tephra disposal site in Perito Moreno following the 1991 Hudson eruption, and the site experienced remobilisation problems (Wilson et al., 2011).

Table 2.4: Reported disposal sites. T = towns/counties/road; A = airport (Sorted by volume collected). Shaded cells indicate what type of disposal site was reported.

Town	Volume collected (m^3)	T/A	Existing waste disposal site	Disposal site specific for tephra						Extra information
				Old quarry	Water body	Secondary uses	Road side	Fields	General Landfill	
Spokane county (St. Helens – 1980)	Not reported	T						■		Fallowed on rural fields
Adams County (St. Helens – 1980)	Not reported	T					■			Private landfills; roadside ditches
Othello (St. Helens – 1980)	Not reported	T	■				■			Abandoned landfill, and private pits and landfills
Spokane city (St. Helens – 1980)	Not reported	T	■							Two large municipal landfills mixed with normal refuse
Manila Int. Airport (Pinatubo – 1991)	Not reported	A						■		Edge of runways and inner fields
Perito Moreno (Hudson – 1991)	Not reported	T					■			Wasteland dumpsites
Guayaquil (Tungurahua – 1999-2010)	Not reported	T	■						■	Las Iguanas landfill site; Island off the coast
Takaharu (Shinmoedake – 2011)	Not reported	T	■							Existing landfill 2-3ha
Takasake (Shinmoedake – 2011)	Not reported	T		■						Old quarry
Anchorage (Spurr – 1992)	Not reported	T	■			■				City dumps, Grit on icy roads
Anchorage Int. Airport (Spurr – 1992)	Not reported	A							■	Fill for low lying areas
Cataina (Etna – 2002)	Not reported	T	■		■		■			Side of road (rural); fill in landfills (City); some in sea
Quito (Reventado – 2002)	Not reported	T	■							Capping of existing landfill
Kagoshima (Sakurajima – ongoing)	Varied	T			■				■	Specific landfill sites in narrow valleys and waterfront land reclamation
State highways (Tongariro – 2012)	None	T					■			Mechanically broomed (sweeper truck) to side of the road
Yogyakarta (Kelud – 2014)	1,500	T						■		Filled in depressions at 4 villages located 5-10km from city
Colfax (Mt. St. Helens – 1980)	13,000	T							■	Three dumpsites – type not reported
Futaleufu (Chaiten – 2008)	30,000	T		■						Abandoned quarry with 4-5m of tephra
Grant County (St. Helens – 1980)	>38,000	T	■				■			Roadside ditches and 20 landfill sites
Grant County Airport (St. Helens – 1980)	45,000	A						■		Spread on fields at airport
Miyakonojo (Shinmodake - 2011)	46,000	T				■			■	Landfill and secondary uses such as bricks and sandbags
Villa la Angustura (PCC – 2011)	95,000	T		■	■					Filled in an old quarry which had turned into a lake
Yakima (St. Helens – 1980)	109,000	T							■	Horse track (25%); low wasteland for city park and sports fields (58%); Private sites (17%)
Ritzville (St. Helens – 1980)	115,000	T		■						Two temporary disposal sites (usually reserved for snow) Area adjacent to airport runway, moved to abandoned basalt quarry
Bariloche (PCC – 2011)	150,000	T		■	■					Old quarry, lake
Moses Lake (St. Helens – 1980)	250,000	T						■		Initially dumped in wetlands Then moved to over 10 other dump sites on vacant lots
Cubi Naval Base (Pinatubo – 1991)	340,000	A						■		Edge of runway (for expansion) & residue spread on field
Chile Chico (Hudson – 1991)	500,000	T	■							Within valley south of city
Los Antiguous (Hudson – 1991)	500,000	T	■							Within valley south of city
Heimaey (Eldfell – 1973)	1,529,109	T			■				■	Land reclamation for airport; landfill for residential siting
Guatemala City (Pacaya – 2010)	11,350,000	T							■	Landfill sites at the edge of city

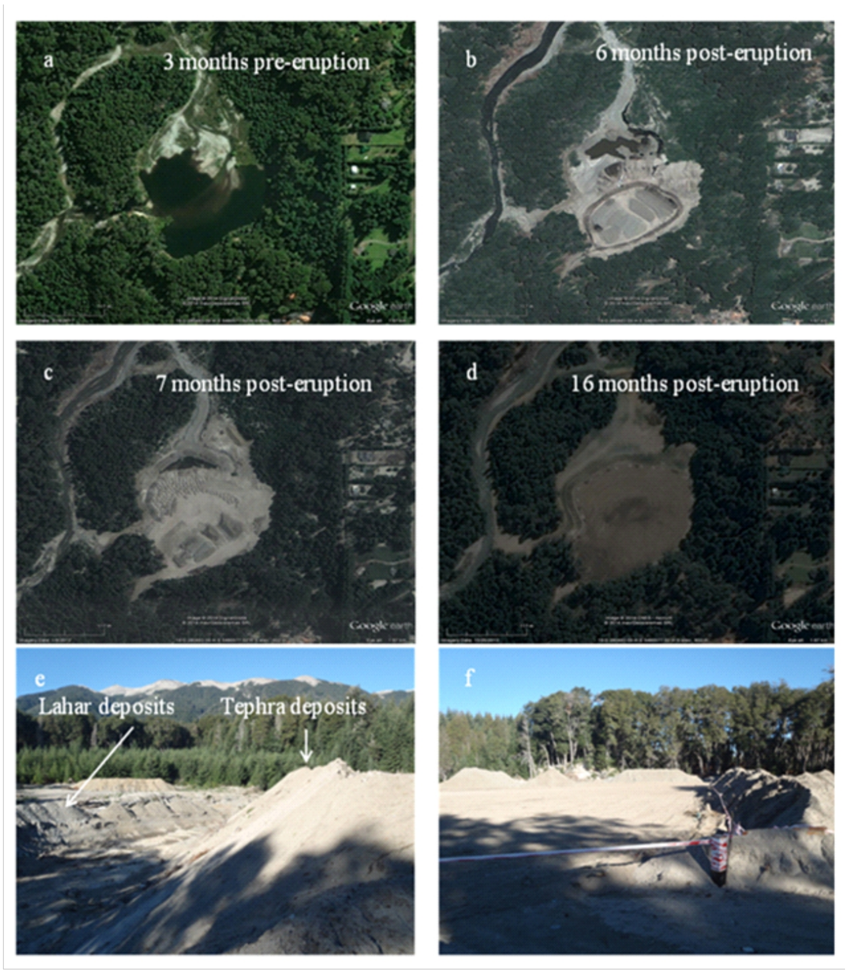


Figure 2.7: Villa la Angostura, Argentina disposal site (PCC): a) Site on 18 March 2011, width of lake at widest point is 180m (credit: Google Earth), b) site on 1 December 2011 (credit: Google Earth), c) site on 6 January 2012 (credit: Google Earth), d) site on 25 October 2013 (credit: Google Earth), e) photo of site March 2012 (photo credit: T.M. Wilson), f) photo of site March 2012 (photo credit: T.M. Wilson)

Table 2.5: Reported tephra stabilisation techniques. T = town/city/county; A = airport (Sorted by thickness)

Town	Thickness of in situ deposit (mm)	T/A	Permanent stabilisation			Chemical dust suppressant	Water	None	Notes
			Soil capped	Vegetated	Bagged				
Merrill Field Airport (Spurr -1992)	3	A	■				■		
Anchorage International Airport (Spurr – 1992)	3	A	■		■				Soil capped
Quito (Reventado – 2002)	3	T						■	Unclear, but unlikely any was undertaken
Takasake (Shinmoedake – 2011)	5-30	T	■						Soil capped
Manila International Airport (Pinatubo – 1991)	10	A			■	■	■		Initially bagged, but then bagging was discontinued and tephra was furrowed and emulsified on fields.
Colfax (Mt. St. Helens – 1980)	13	T	■						Soil capped
Spokane city (St. Helens – 1980)	16	T			■				Sawdust and bagged. No stabilization at the disposal sites.
Perito Moreno (Hudson – 1991)	20	T						■	No stabilisation undertaken
Yogyakarta (Kelud – 2014)	20	T	■						Soil capped
Othello (St. Helens – 1980)	22	T	■						Top soil
Grant County Airport (St. Helens – 1980)	25	A		■					Grass growth
Grant County (St. Helens – 1980)	25	T				■			Rock salt on roads, no stabilization at landfill sites
Jacobacci (PCC – 2011)	50	T		■					Building materials, plans to vegetate
Adams County (St. Helens – 1980)	60	T				■			Lignin sulphate on roads and ditches
Moses Lake (St. Helens – 1980)	60	T	■						1 inch of topsoil
Spokane county (St. Helens – 1980)	60	T				■			32% calcium chloride
Yakima (St. Helens – 1980)	70	T	■	■					Soil capped, irrigated and rye grass planted
Ritzville (St. Helens – 1980)	100	T	■	■					Top soil and grass
Chile Chico (Hudson – 1991)	100	T	■	■					Soil capped and grassed
Los Antiguous (Hudson – 1991)	100	T	■	■					Soil capped and grassed
Cubi Naval Base (Pinatubo – 1991)	200	A	■	■		■	■		Bulk tephra capped and vegetated. Residue swept to infield and sprayed with asphalt emulsion
Heimaey (Eldfell – 1973)	300	T	■	■					Soil capped and vegetated (fertilizer and grass seed dropped from aircraft onto tephra)

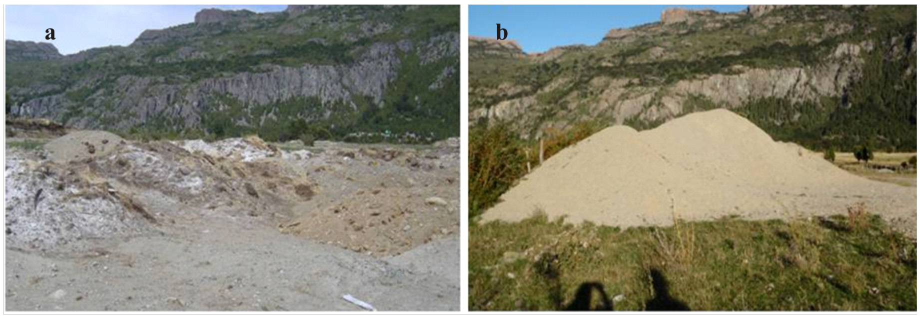


Figure 2.8: Comparison of ash disposal site for Chaiten in a) 2009 and b) 2012 indicating stabilisation by vegetation

2.5 Discussion

The case studies reviewed here indicate that tephra clean-up operations are complex. Multiple factors influence tephra clean-up methodologies and performance (Blong, 1984; Wardman et al., 2012; Wilson et al., 2012, 2013; Magill et al., 2013). The factors which broadly influence tephra clean-up include: the volume and characteristics of tephra; the likelihood/uncertainty of further tephra falls; sources of remobilisation (climatic and anthropogenic); the land-use of the receiving site; and the social context (e.g. planning and experience) (Figure 2). These factors make specific thresholds (such as decisions to clean-up different surfaces) unique to each urban area.

Influence of the physical properties of tephra on clean-up

Physical properties of tephra (grain size, mechanical strength, moisture, cementation, abrasiveness, mineral composition, morphology, and leachable elements) can impact clean-up operations by: being difficult to physically remove from surfaces, remobilising and impacting previously cleaned surfaces, and damaging clean-up surfaces and machinery (Table 2.6).

Unlike many other natural events which have a relatively clear start and end point (such as tsunami or floods), volcanic eruptions have variable durations from minutes to decades and can result in multiple instances of tephra fall on a community. This presents a challenge to authorities, as they must decide when to begin clean-up operations. If clean-up operations begin too early there is the possibility of having to clean surfaces many times due to ongoing tephra falls and remobilisation. This reduces efficiency and increases costs. However, delaying clean-up can also lead to impacts which would not have occurred if clean-up began immediately following deposition (e.g. damaged water pipes). Therefore, clean-up planning should consider the likely physical properties of tephra to:

- determine when clean-up should begin;
- determine resource requirements;
- prevent remobilisation;
- minimise damage to the surface being cleaned.

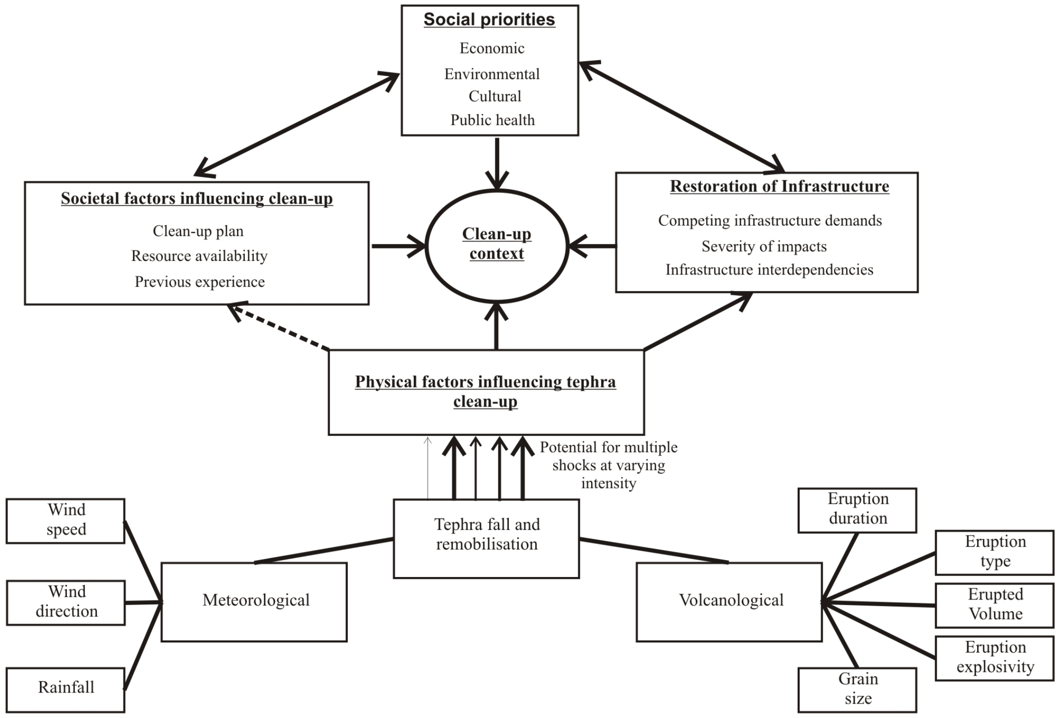


Figure 2.9: Factors influencing tephra clean-up

Table 2.6: Tephra properties influencing clean-up operations

Tephra property		Explanation
Grain size	Coarse	Low potential for remobilisation
	Fine	High potential for remobilisation
Mechanical strength	Low	Can be broken into smaller particles by vehicles increasing potential for remobilisation
Moisture content	High	Saturated and difficult to remove; when dried becomes cemented to surfaces
	Medium	Binds particles together reducing the potential for remobilisation
	Low	Increased demand on water resources due to water needed to prevent remobilisation
Abrasiveness	High	Damage clean-up machinery (e.g. street sweepers) and surfaces (e.g. roads)
Thickness	High	Requires heavy machinery to remove bulk material
	Low	Requires street sweepers to remove residue material

2.5.1 Influence of community and urban area characteristics on clean-up

Total volumes of tephra removed vary depending on types of surfaces affected (e.g. roads, roofs, vegetated), the land uses of the affected area and the tolerance of the community to residual (and remobilised) tephra. Tephra thickness of 1 mm results in obscured road markings and a reduction of traction between wheels and the road surface leading to hazardous driving conditions, suggesting a logical threshold to begin clean-up of sealed roads (Wilson et al., 2012). However, 1 mm of tephra on a grassed area is unlikely to cause noticeable impacts, meaning that stabilisation rather than removal of tephra would be appropriate.

The social context of tephra affected communities can lead to varying experiences of tephra fall clean-up:

- Different communities will have different tolerance levels for particulate matter within the urban environment. For example, a community which experiences regular dust storms might have higher tolerance levels and therefore not feel as great a need for extensive clean-up operations as areas where particulate matter concentrations are strictly controlled.
- Communities that have a clean-up plan will have a more efficient clean-up operation because lines of communication between authorities will have been established and resource requirements identified (e.g. Guatemala city; Wardman et al., 2010, and Kagoshima; Durand et al., 2001).

- Social values and priorities of the impacted communities are very important as these values will dictate how economic, environmental, public health and cultural priorities will be balanced during planning and response to tephra fall.

Interactions between both physical and social characteristics means that tephra clean-up in urban environments is highly context specific. Adopting a local clean-up plan will be of benefit to communities by allowing a community to understand the local context for tephra clean-up.

2.5.2 Proposed scale of response

Although specific thresholds of tephra accumulation for determining clean-up response will be community-specific, assessing relationships between tephra accumulation, volume removal, and clean-up methods, a broad scale of response can be determined. Depending on tephra accumulation levels, different surfaces (roads, roofs, footpaths, vegetated areas) within an urban environment will require clean-up and tephra removal (Table 2.7). At trace levels of tephra (<1,000 m^3/km^2) coordinated clean-up operations might not be necessary (e.g. Anchorage - Redoubt 2009, and Te Maari - 2012). At low tephra accumulations (1,000 m^3/km^2 10,000 m^3/km^2) coordinated tephra removal from roads is usually undertaken, such as in Portland, Oregon following the eruption from Mt. St. Helens in 1980. Tephra volumes on individual properties are usually quite low at these accumulations, and as such, property owners can usually cope without assistance from local authorities for tephra removal. Moderate accumulation levels (10,000 $m^3/km^2$50,000 m^3/km^2) require coordinated clean-up operations to remove tephra from roads, and private properties owners will need to remove tephra from their properties as volumes will likely exceed the level with which they can add to gardens. There will likely be increased demand for heavy earth moving machinery and trucks. Private property removal can either be assisted by local authorities or outsourced to private clean-up operators. At high accumulation levels, most surfaces within an urban environment will require tephra removal because of potential impacts such as building damage. This will call for a comprehensive coordinated approach to clean-up operations, and management of large workforces. However, tephra removal in areas of land that is very heavily impacted (e.g. parts of Heimaey) might not be considered an immediate response priority or could be considered too expensive and cumbersome to conduct as part of the recovery phase.

Table 2.7: Clean-up of surfaces at various accumulation levels (Trace accumulation image credit: Grant Wilson; Low accumulation image credit: Christina Magill; Medium accumulation image credit: Christina Magill; High accumulation image credit: Ailen Rodriguez)

Accumulation	Clean-up surfaces	Images
Trace (<1,000m^3/km^2)	No removal of tephra from properties, only minor clean-up (sweeping of roads). Removal of tephra from airport runways will be required.	
Low (1,000m^3/km^2 – 10,000m^3/km^2)	Coordinated clean-up of sealed roads in urban areas, and airports. Private properties can mostly cope without assistance. Assistance required for some community groups, such as the elderly.	
Medium (10,000m^3/km^2 – 50,000m^3/km^2)	Coordinated clean-up of all roads, and assistance with private property clean-up (e.g. bag distribution or road side collection). Management of large volunteer work forces could be required.	
High (>50,000m^3/km^2)	Coordinated clean-up of all impervious surfaces and some recreational areas (e.g. parks). High demand for heavy earth moving machinery (e.g. loaders, graders).	

2.5.3 Implications for impact assessments

Previous studies that have assessed clean-up impact made assumptions regarding volume of tephra removed from urban environments. Paton et al. (1999) assumed that either the total volume of tephra fall on an urban would be removed, or only road surfaces would have tephra removed. Magill et al. (2006) assumed that properties with tephra volumes less than 1 m^3 would not remove tephra. Both Paton et al. (1999) and Magill et al. (2006) assumed that 100% of tephra will be removed from the surfaces which are cleaned. This chapter has contributed to the impact assessment and response planning discourse by providing a comprehensive evidence base of tephra fall clean-up operation experiences. The findings in the analysis provided in this chapter indicate that it is important to consider tephra accumulation and local context when estimating volume and cost of tephra removal from urban environments. When tephra accumulation is low (1,000 m^3/km^2) it is appropriate to assume that only roads would have a coordinated clean-up. As tephra accumulation increases other urban surfaces could be included (e.g. roofs or driveways).

2.5.4 Research gaps

A critical aspect of volcanic risk assessment is the quantification of probable impacts on urban environments. Despite the importance of tephra clean-up operations to restoring urban functionality and recovery from tephra fall events, there is a lack of quantified tephra clean-up impact assessments on urban communities. Such studies could be done utilising geospatial modelling of urban environments to determine estimates of the amount of tephra that will need to be removed.

There is limited knowledge of thresholds that influence different clean-up methodologies. Therefore, information from technical experts regarding efficiencies of clean-up machinery for different physical characteristics of tephra fall would be of great value. To better understand duration of clean-up operations, an understanding of how efficient different types of machinery are at various tephra fall thickness and grain sizes is necessary.

There are complex social, economic and political issues associated with tephra clean-up, particularly around land retirement and disposal site selection. Planning for clean-up in almost never conducted. Pressure to restore urban functionality by removing tephra from urban environments quickly causes disposal sites to be selected without the same rigour that could be applied before tephra fall. This leads to uncertainty about long term impacts of tephra disposal sites. Longitudinal studies about the impacts of tephra disposal sites on communities would be beneficial.

An even more complex issue is land retirement. It is straightforward to decide to clean high value areas where clean-up would not be difficult. Equally, decisions not to clean areas of low value and experiencing little impact from tephra would be straightforward. A large area of uncertainty and complexity is areas where a decision to clean-up is not obvious. For instance, in extremely high accumulation tephra falls (e.g. Heimaey), at what point do costs of removing tephra outweigh the benefits?

Generic clean-up plans are useful in the context of establishing lines of communication between relevant authorities. However, they are likely to be of limited use without considering context specific conditions of the local environment. This would require identifying potential sources of tephra fall and tephra characteristics as well as considering resource availability and community values. Clean-up plans which address specific community characteristics would be of great benefit for communities at risk of tephra fall.

Chapter 3

Quantitative impact assessment of tephra clean-up in Auckland

Essentially, all models are wrong, but some are useful.

George E. P. Box (1919-2013)

3.1 Introduction

Clean-up operations can help mitigate impacts from tephra fall and pyroclstic flow deposits in urban environments by removing the material to an area where it can be stabilized. They assist in reducing health hazards, restoring essential service and socio-economic functionality, and even restore habitability to severely affected areas. However, clean-up operations can be complex, resource intensive, expensive, and often context specific (e.g. prior planning, grain size, deposit thickness, rainfall) (Chapter 2). Review of previous tephra fall clean-up operations in urban environments highlights that they are rarely planned for, leading to inefficient and costly operations (Chapter 2). It has been recognised that effective disaster risk management involves planning for disaster waste management (Brown et al., 2012).

Planning for tephra clean up operations requires assessing:

- volcanic hazards likely to effect the urban environment;
- available resources for clean up and transportation;
- transportation distance between clean-up and disposal sites;
- availability and operational capacity of disposal sites;

- understanding social requirements for clean-up (e.g. environmental regulations);
- understanding economic implications for clean-up (e.g. benefit-cost of cleaning up).

In the case of Auckland, New Zealand, there is strong justification to plan for tephra clean up due to the importance of the city to the New Zealand economy and the potential for a range of tephra hazard scenarios. Tentative plans developed in 2001 identified potential disposal sites and volumes of tephra requiring removal(Johnston et al. 2001). However, due to increased data availability (volcanic impact assessment reconnaissance trips, and geospatial information) it is important to re-assess these plans.

The objective of this chapter is to develop a quantitative tephra clean-up model for Auckland, New Zealand, which can be used to aid response and recovery planning. The model will be developed to consider coordinated clean-up operations conducted by municipal authorities. The model's design is informed by the review of previous urban tephra fall clean-up operations in Chapter 2. A range of volcanic eruption scenarios which deposit different volumes of tephra on Auckland city from both proximal and distal sources are used to demonstrate the utility of the model.

First, this chapter presents the methodological approach used to develop a tephra clean-up impact model. This includes:

- development of an inventory of surfaces potentially requiring clean-up following tephra fall and pyroclastic flow within Auckland;
- network modelling to determine time to disposal sites (based on Auckland Volcanic Field Contingency Plan tephra disposal sites);
- clean-up cost model development, clean-up duration model development;
- probabilistic modelling to manage uncertainty.

Scenarios are then used to test the model and assess potential clean-up impact in Auckland. Model results present estimated volumes of material requiring clean-up, duration of clean-up, cost of clean-up, and benefit-cost of clean-up. A critical discussion of the model and modelling results is then presented for the purpose of assessing viability of model results. Finally, a discussion of implications for clean-up response and recovery planning to tephra fall and pyroclastic flow in Auckland City is presented.

3.2 Methods

In order to model tephra clean-up impact to Auckland it is necessary to consider three major components: (1) hazard, (2) vulnerability, (3) exposure (Figure 3.1). For simplicity, a deterministic approach to hazard assessment was conducted to determine the potential footprint, magnitude, and sources of tephra that could impact Auckland. A geospatial exposure inventory is created to combine hazard scenarios with different surfaces (e.g. roads, roofs) in Auckland. Informed by the evidence base established in Chapter 2, tephra removal volumes can be determined to give model results of cost and duration of clean-up.

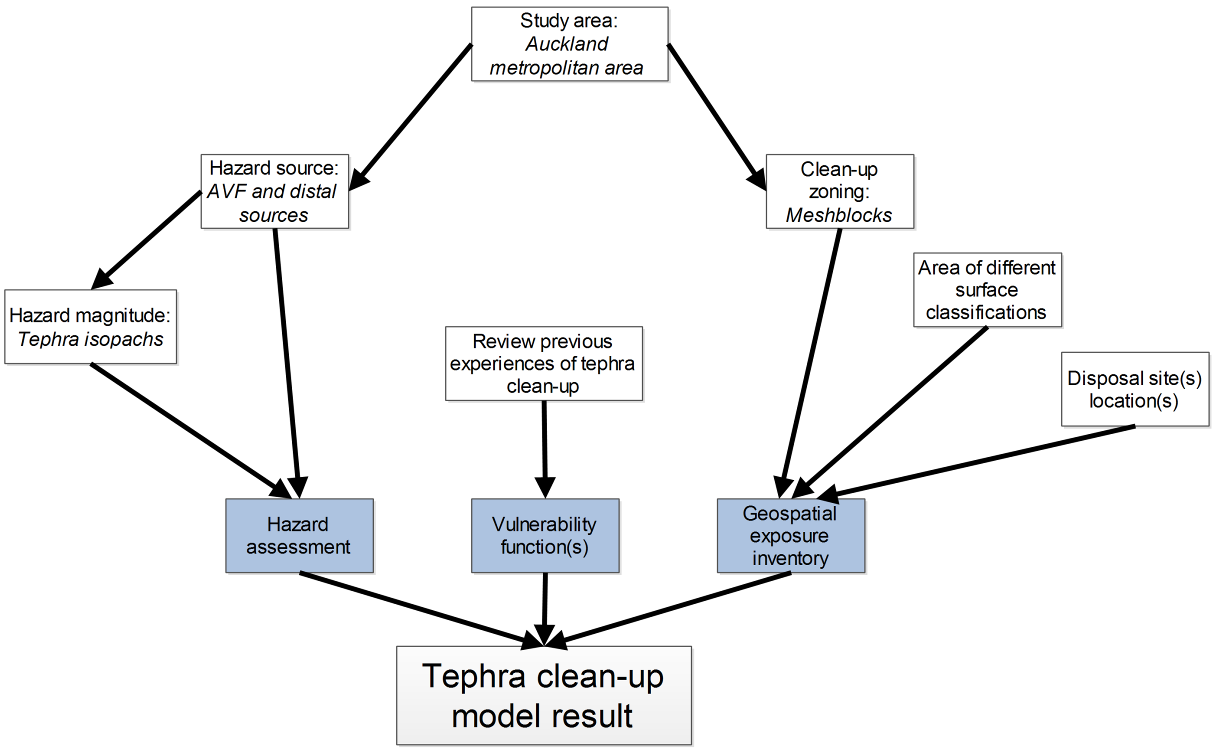


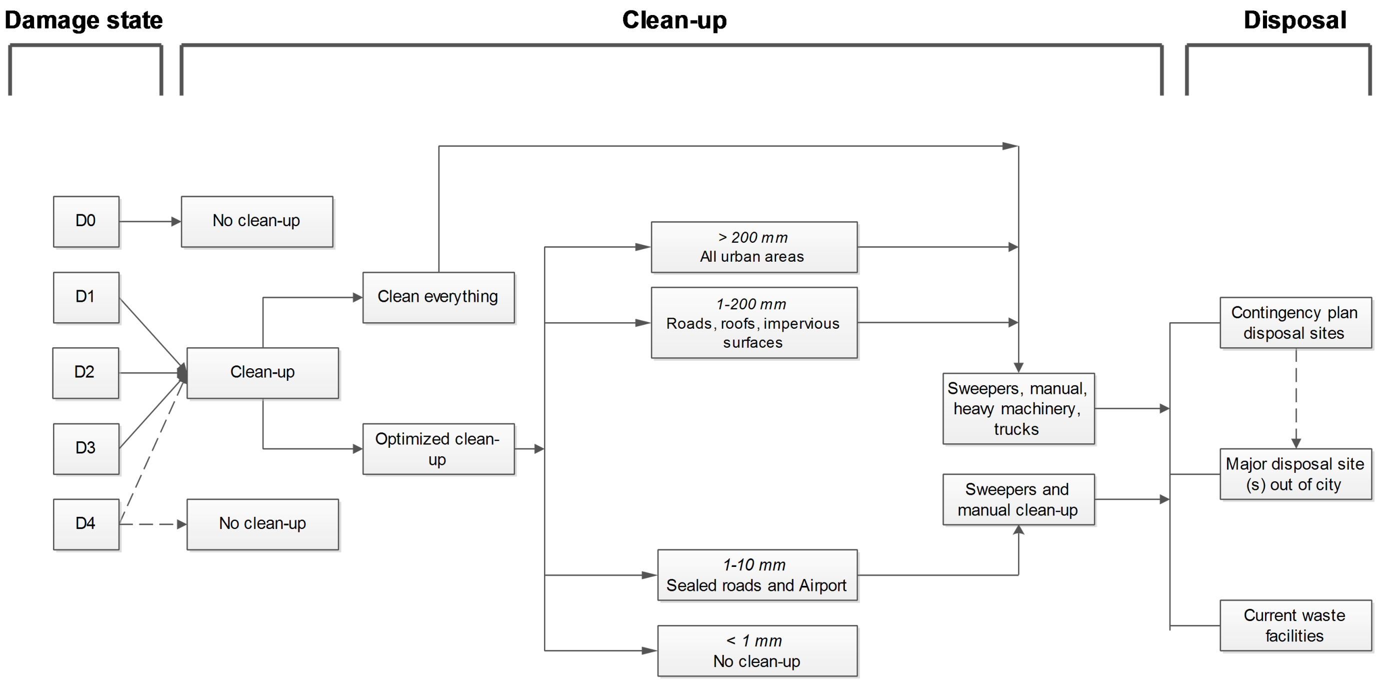
Figure 3.1: Tephra clean-up model conceptual framework

Vulnerability was determined by assessing previous clean-up operation experiences to determine potential thresholds of tephra accumulation for clean-up of different surfaces. The scale of clean-up response to tephra fall depends on the severity of tephra accumulation, as established in Chapter 2. Very large tephra falls require almost total clean up of the deposit from all surfaces to restore urban functionality (i.e. >200 mm). However, more modest accumulations of tephra (e.g. 10 - 200 mm) may only require impervious surfaces to be cleaned, such as roads and roofs, which reduces the total tephra volume required to be cleaned (Chapter 2). Very thin tephra accumulations (i.e. 1 mm) typically only requires a coordinated road clean-up operation (Chapter 2). Determining the area within an urban environment these surfaces occupy is an important aspect of developing a tephra clean-up model. Clean-up response (thoroughness of clean-up and resource requirements) is likely to be dependent on the level of tephra accumulation within the urban area (Chapter 2).

Based on evidence presented in Chapter 2, a conceptual framework has been developed to determine what surfaces should be cleaned under a coordinated clean-up response (Figure 3.2). Trace amounts of tephra deposits (<1 mm) will likely result in very few impacts to urban functionality, and no coordinated clean-up response will be required. With more than 1 mm of tephra deposited, roads will likely be the first infrastructure to be impacted, requiring a coordinated clean-up operation to be initiated. Based on previous tephra fall clean-up operations it is anticipated that a coordinated clean-up of private properties will not be required, as private property owners can either clean-up themselves or hire contractors to assist with clean-up. A similar approach was taken after Mt. Ruapehu eruptions of 1995-96 where only roads and Rotorua CBD were cleaned as part of a coordinated clean-up response (Johnston et al., 2000). As thickness increases to >10 mm, so too will volumes in individual properties. This larger volume is likely to exceed what individual property owners can cope with and will require assistance from municipal authorities. With >100 mm buildings will begin to experience non-structural and structural damage (Jenkins et al. 2014b). Ideally roofs will be cleaned before such a thickness accumulates. With thickness >1,000 mm the potential for land retirement increases as it becomes less likely to be cost effective to clean-up and reinstate physical infrastructure (Jenkins et al. 2014b).

Disposal sites are an integral aspect of tephra clean-up operations as they provide a permanent site for immobilisation of tephra deposits. Broadly, there are three options for disposal of tephra in Auckland.

- Current waste disposal facilities
- Establish a large disposal site outside of city
- Marine disposal
- Auckland Volcanic Field Contingency Plan disposal sites



	Indicative thickness	
D0	*< 1mm*	No reduced functionality
D1	*> 1 mm*	Reduced road traction, obscured road markings, airport runway closure
D2	*> 10 mm*	Pyroclastic volumes in private properties necessitate assistance from municipal authorities to remove
D3	*> 200 mm*	Structural and non structural damage to buildings
D4	*> 1,000 mm*	Land or assets beyond repair

Figure 3.2: Conceptual diagram of clean-up process

There is potential that current waste disposal facilities (e.g. Claris, Whitford, Redvale, and Hampton Downs landfills) will be inappropriate for use as tephra disposal locations because of the large volumes of material needing to be disposed (Johnston et al. 2001). A large disposal site outside of the city would allow for large volumes of material to be disposed, although, no such site has currently been identified. Similarly, tephra could be disposed in marine areas, however, no such options have been investigated and it has been suggested that the costs of marine disposal could be an order of magnitude higher than land based disposal (Johnston et al. 2001). Dolan et al. (2003) identified 16 potential sites for tephra disposal within Auckland metropolitan area, which have since been adopted into the Auckland Volcanic Field Contingency Plan. This thesis also adopts these disposal sites within the tephra clean-up model.

A geospatial exposure inventory was created to model tephra volumes on different urban surfaces (e.g. roads, roofs) and to run a network analysis for transportation of tephra to disposal sites. This involves first sectioning Auckland metropolitan area by Meshblocks (Mb), as it is likely that clean-up will be organised on a similar spatial scale. A similar approach to clean-up of fine sediment in an urban environment was in Christchurch where impacted areas were sectioned into zones for clean-up teams to remove liquefaction ejecta in response to the Canterbury earthquake sequence of 2010-2011 (Villemure, 2012). Once Auckland's metropolitan area was sectioned, the area within each zone that was made up of different surfaces that required clean-up was determined (informed by Figure 3.2). This then allows determination of the total volumes of tephra that need to be removed which can inform duration and cost models.

3.2.1 Geospatial exposure inventory

Geospatial analysis is used to determine impervious surface area from a range of data (Table 3.1). This approach allows for easy assessment of removal volumes and transportation time to a range of disposal sites. Area within each Mb made up of building footprint (proxy for roof area), road, and other impervious surfaces is determined by spatially joining (ArcToolbox operation) the meshblock shapefile with the different urban surface data sets (Figure 3.3). Road, building footprint and impervious surfaces shapefiles have be sectioned at Mb boundaries to ensure that overlaps between different Mb are not present. Failure to do so can result in over calculating urban surface areas where surfaces traverse multiple Mb polygons (e.g. roads).

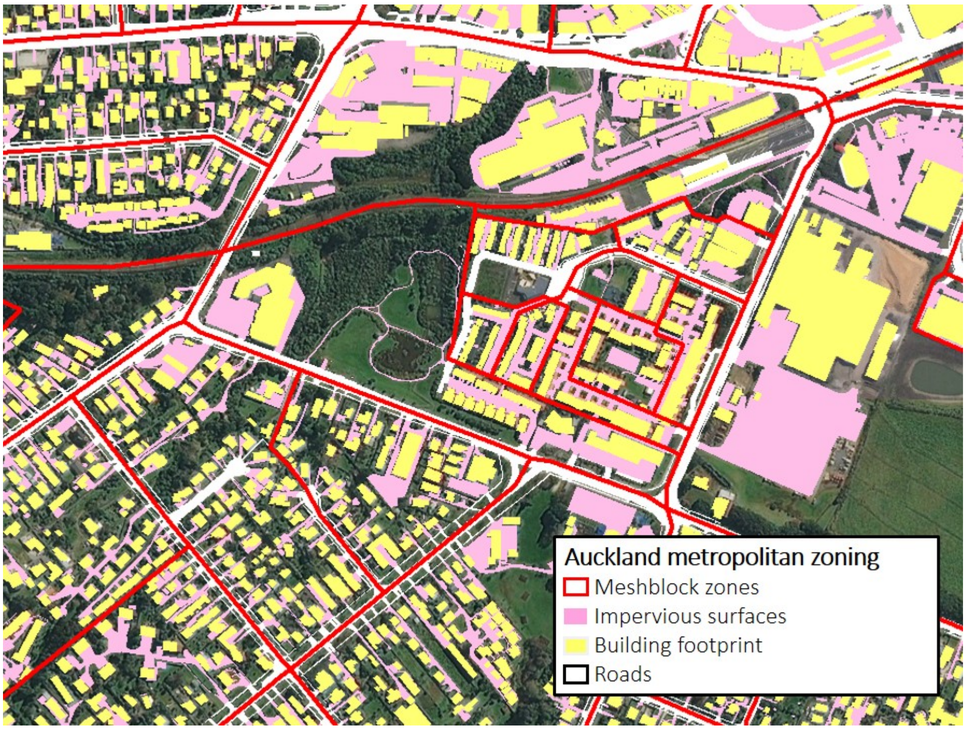


Figure 3.3: Example of impervious surface classification in the Auckland metropolitan area

Table 3.1: GIS data and data sources

Data	Source
1:100 Flood polygon	Auckland Council Geospatial Team
Auckland Building Footprint	Auckland Council Geospatial Team
Auckland Impervious Surfaces	Auckland Council Geospatial Team
Auckland Rate Assessment	GNS Science
Draft Unitary Plan (2013)	Koordinates.com
NZ Meshblocks (2012 annual pattern)	Koordinates.com
Terralink Road Network	Auckland Council Geospatial Team

3.2.2 Tephra clean-up modelling

3.2.2.1 Origin-Destination network modelling

Origin-destination (OD) cost matrix modelling was done in ArcGIS 10 to determine transport time and distance from Mb to disposal sites. Random points assigned (using Create Random Points - data management tool) to each Mb are used as pick-up points (origins) for trucks to transport material to disposal sites (destination) (Figure 3.4) because exact pick-up points are unknown. OD cost matrix modelling will assess the cost (time and/or distance) from each origin to each possible destination.

In order to simplify analysis, speed limits for each section of road were used to determine hauling time between pick-up points and disposal points, and so hauling times do not consider the influence of traffic. In this analysis disposal sites from the Auckland Volcanic Contingency Plan are used, and disposal sites are allocated to Mb based on results from OD modelling for the shortest amount of time from an origin point to a destination. The reason disposal sites are allocated this way is to minimise the potential for remobilisation of tephra, either by slow clean-up or by blowing out of trucks during transportation. Due to a lack of site specific designs for the identified disposal, the model assumes that identified disposal sites have the volumetric capacity to handle the volumes of material required. Disposal sites within evacuation zones are removed from this analysis as it is unlikely they will be functional for an immediate clean-up response, although they may become viable once the evacuation zone is lifted or reduced.

Figure 3.4: Example of origin and destination points

3.2.2.2 Clean-up cost

This section explains the development of the model to assess cost of clean-up operations. The clean-up cost relationships for discrete tephra fall presented in Chapter 2 yield poor correlative relationships between cost and tephra accumulation because of uncertainty regarding contributors of cost (machinery hire, transportation, disposal, workforce) and are therefore not appropriate for use here. Alternatively, Johnston (2001) used a rate of $21/m^3 (adjusted to 2014 NZD using Reserve Bank Inflation

Calculator) assuming a disposal site was located 50 km from pickup points. This equates to approximately 45c per m^3 per km to disposal sites, but only considers transport costs. Cost for disposal of material could also be large and should be considered. Johnston et al. (2001) used a rate of \$4 per m^3 (adjusted to 2014 NZD using Reserve Bank Inflation Calculator). This model was also used to assess clean-up cost of liquefaction ejecta from the 2010-2011 Canterbury earthquake sequence (Villemure, 2013). When accounting for the distance to the disposal site, transportation and disposal of liquefaction ejecta came to approximately NZ\$ 10 per m^3. The total cost of liquefaction ejecta clean-up (including volunteer time, contractor costs, transportation, disposal, disposal site maintenance, and donations) came to some NZ\$ 40,000,000 (or NZ\$ 78 per m^3). However, it should be noted that contractor costs varied widely (approximately NZ\$69/hr to NZ\$91/hr) between the 3 major clean-up operations that were required (Villemure, 2013). Liquefaction ejecta clean-up efficiency (volume removed per operation) varied between all the clean-up operations which results in a large discrepancies between the cost/m^3 of each operation. This suggests that there are hidden complexities when attempting to assess disaster clean-up costs. For simplicity this research only considers transportation and disposal costs (Equation 3.1).

$$NZD = (0.45 \cdot m^3 \cdot km) + 4 \cdot m^3 \tag{3.1}$$

Where:
NZD = Cost of transportation and disposal
m^3 = volume of tephra in cubic metres
km = Kilometres to disposal site

In heavily impacted areas (e.g from base surge or heavy tephra fall) there is potential that the costs of clean-up could exceed the benefits of cleaning up. Therefore, a simple benefit-cost analysis for clean-up of various zones is included. The intention of this analysis is to determine if economic viability of clean-up could be an issue to consider for recovery planning. This is undertaken by taking the value of the land and dividing it by the cost of clean-up. Land value is chosen instead of capital value because it is likely that in heavily impacted areas such as those impacted by base surge or heavy tephra fall will be heavily damaged or destroyed. To simplify the analysis, costs associated with these structures will be assumed to be dealt with through insurance processes. Land value data is sourced from the 2011 Quotable Value (QV) land valuation. While more recent data has recently been released by QV, data is not available in a geospatial format in time to be utilised within this research project. Therefore, to adjust values to 2014 NZ$ an addition 30% (average increase in capital values since 2011; Auckland Council, 2014) is added to the 2011 values. If benefit-cost ratios are close to or <1, then retirement of land could be a potential post disaster management option and should be considered within disaster recovery plans. However, a more detailed analysis including social, environmental, political, and economical factors is required at a site specific scale before retirement of specific parcels of land is determined.

3.2.2.3 Determining clean-up duration for transportation of tephra by dump truck

This subsection derives an equation for clean-up duration of areas using dump trucks to transport material to disposal sites. The model is developed based on the assumption that clean-up duration is dependent on the time it takes to transport tephra from pickup points to disposal sites, and that the following activities occur:

1. Tephra is moved from properties to road sides
2. Earth moving machinery then consolidate tephra into piles at pickup points where it is loaded onto trucks
3. Trucks then transport tephra to disposal sites

Further model assumptions and limitations are discussed in detail in Section 3.4.

The time it takes to complete clean-up therefore depends on the number of trips to move material to disposal sites and how long each trip takes to complete. The number of truck trips will depend on the volume capacity of the trucks within the fleet. The duration of each truck trip depends on:

- time to load trucks
- time to haul tephra from pickup points to disposal sites
- time to unload tephra at disposal sites
- time to return to a pickup point to be reloaded

Truck loading time depends on the required number of bucket swings from a loader to fill a truck (Figure 3.5), which depends on the capacity of the bucket on the loader and capacity of the truck being loaded (equation 3.2; Peurifoy & Schexnayder, 2002).

(a) Start of bucket cycle

(b) End of bucket cycle

Figure 3.5: Loading trucks with tephra deposits near Merapi Volcano, Java, Indonesia

$$Bs = Tv/Bv \tag{3.2}$$

Where:
Bs = Bucket swings to fill truck
Tv = Truck volume
Bv = Bucket capacity of loader

In practice it is not efficient to light load (scoop up less that 100% of a bucket capacity) to match the exact volumetric capacity of a truck (Peurifoy & Schexnayder, 2002). This means that Bs has to equal an integer which can either be rounded down (less bucket loads and less volume per truck) or rounded up (excess spills off truck). In this analysis Bs is rounded up to ensure full trucks are used. Peurifoy & Schexnayder (2002) suggest loading time can then be determined as per equation 3.3

$$L = Bs \cdot Bc \tag{3.3}$$

Where:
L = Loading time
Bs = Bucket swings
Bc = Bucket cycle time

Truck cycle time indicates the time it takes for a truck to complete a cycle of removal: (1) load, (2) travel to disposal, (3) spotting and queuing at disposal site, (4) unload, and (5) return trip. Cycle time can be estimated based on equation 3.4 (adapted from Peurifoy & Schexnayder, 2002). Spotting and queuing times are going to be dependant on operational capacity of disposal sites (number of trucks a disposal site can accept per hour or day).

$$Tc = L + (H \cdot 2) + S + U \tag{3.4}$$

Where:
Tc = Truck cycle time
L = Loading time
H = Hauling time
S = Spotting and queuing time
U = Unloading time

Clean-up operation duration can then be estimated by the total time it takes to transport material from source points to disposal sites (Figure 3.5), and by accounting for the hours per day that transportation of material would be done (Equation 3.6).

$$D = (2 \cdot (Fleet\ hauling\ time\ per\ cycle) \cdot cycles) + (Loading\ and\ unloading\ time \cdot cycles) \tag{3.5}$$

$$D = \frac{(2 \cdot (Fleet\ hauling\ time\ per\ cycle) \cdot cycles) + (Loading\ and\ unloading\ time\ \cdot cycles)}{hrs/day} \tag{3.6}$$

Where:
hrs/day = hours per day of operation

3.2.2.4 Determining clean-up duration for clean-up using street sweepers

Like dump trucks, street sweepers have a set volumetric capacity with which they can collect material. However, they collect material by sweeping across a surface and not from specific pick-up points (See Appendix 1 for sweeper truck details). Therefore, duration for clean-up using street sweepers requires an adjusted equation to account for this.

The total amount of sweeper runs (trips to disposal sites) is related to the capacity of sweeper truck and total volume of material on roads

$$R = Q/c \tag{3.7}$$

Where:
R = sweeper runs
Q = volume to remove from roads (km^3)
c = average capacity of sweeper truck (km^3)

Sweeper trucks have been reported to have efficiencies of removing fine particles of between 10 - 60% (Depree 2011). Therefore it is important to consider how efficiency will influence clean-up times.

$$E = 100/e \tag{3.8}$$

Where:
E = Efficiency factor
e = Percentage of material picked up from roads after 1 run over a surface

It is then possible to determine the distance a sweeper truck can travel before reaching capacity (Equation 3.9). The volume of tephra for each metre of a road lane swept will be approximately 0.0035 m^3

$$km = \frac{\frac{c}{0.0035}}{1,000} \cdot E \tag{3.9}$$

Where:
km = kilometres a sweeper can travel before reaching volumetric capacity
c = Capacity of sweeper truck (m^3)
E = Efficiency factor

Therefore duration of sweeping operations to remove thin levels of tephra from road surfaces can be defined as

$$D = \frac{((((R \cdot km)/V)/a) \cdot E) + (R \cdot T)}{Tn} \tag{3.10}$$

Where:
D = duration of clean-up in days
R = Sweeper runs
km = Kilometres a sweeper can travel before reaching volumetric capacity
V = Speed of sweeping (km/hr)
a = Hours per day of sweeping
E = Efficiency Factor
T = Average time to a disposal site
Tn = Total number of trucks available

3.2.2.5 Monte Carlo modelling

Uncertain model parameters are a common aspect of modelling processes such as post-disaster response and recovery. Monte Carlo methods are commonly used for the purpose of simulating uncertain input variables and to include uncertainty within models in a transparent manner (Hurst & Smith, 2004; Wang et al., 2008; Yu et al., 2013). This allows for statistical distributions to be chosen for each input variable, and all possible outcomes to be modelled, resulting in a probability distribution of different outcomes. This makes Monte Carlo simulation an ideal method to deal with aleatoric uncertainty within the duration and cost models. Monte Carlo was conducted by running 10,000 iterations (required to obtain smooth curves) of duration (Figure 3.6) and cost (Figure 3.7) models using input parameters presented in Table 3.2.

The distance a street sweeper can travel before reaching capacity will depend on the volume of material on a section of road and the sweepers ability to pick up material. Efficiency of street sweepers to removing fine grained material varies depending on sweeper type and grain size of material being removed. Removal efficiencies in real world conditions have been measured as being as low as 10% (Selbig & Bannerman, 2007). In Portland following the Mt. St. Helens 1980 eruption, sweepers were reported to be only removing about 50% of fine grained (median grain size 31 microns; Shulters & Clifton, 1981) material on roads. It was assumed that sweeper efficiency factors would be between 1-100 with 2 (50%) being the most likely efficiency. Cost of sweeping has been reported to be between NZ$ 45-90 per curb-kilometre (km of road lanes requiring cleaning) depending on the type of sweeper (Schilling, 2005). Due to unknown street sweeper resources (type and amount) assumptions had to be made regarding sweeper volume capacities, number of sweeper trucks, and speed of street sweeping. Typical street sweeper volume capacities are between 5-7 m^3 (Schilling, 2005). Although the number of street sweepers has not been confirmed by Auckland Council, it is assumed by the author to be in the range of 5-20 with 10 being the most likely number. The speed of sweeping was based on sweeping best practice guidelines suggesting speeds of between 5-7 km/hr (Sutherland & Kidwell-Ross, 2010).

Truck types and body volumes are based on common truck types suggested by Villemure (2013). The number of trucks available for clean-up purposes is unknown as it is likely that Auckland Council will need to utilise privately operated trucks to assist with clean-up. Here, it is assumed that at least 1 of each truck type is available and that a maximum of 100 of each is possible, with 50 of each being the most likely. Truck unloading times are likely to be variable depending on the conditions at a disposal site (e.g. space to manoeuvre). Peurifoy & Schexnayder (2002) suggest that unloading times are approximately 1.5 minutes for rear-dump trucks. But it is important to consider that disposal sites identified within the Auckland Volcanic Field Contingency Plan are almost entirely recreational parks, and so are not designed for the movement of dump trucks and other heavy machinery. Therefore, it is assumed that dumping time will be at least 2 minutes, a maximum of 10 minutes and most likely 5 minutes.

It is assumed that transportation of material will occur from 12-24 hours per day. A higher weighting has been given to 12 hours per day because disposal sites are located in residential areas, making a 24 hour operation potentially unacceptable to residents living near disposal sites or along transportation routes. Distance to disposal sites is going to vary depending on what disposal sites are available. A range of 3-20 km was chosen for distance to disposal sites, with the most likely distance being 5 km.

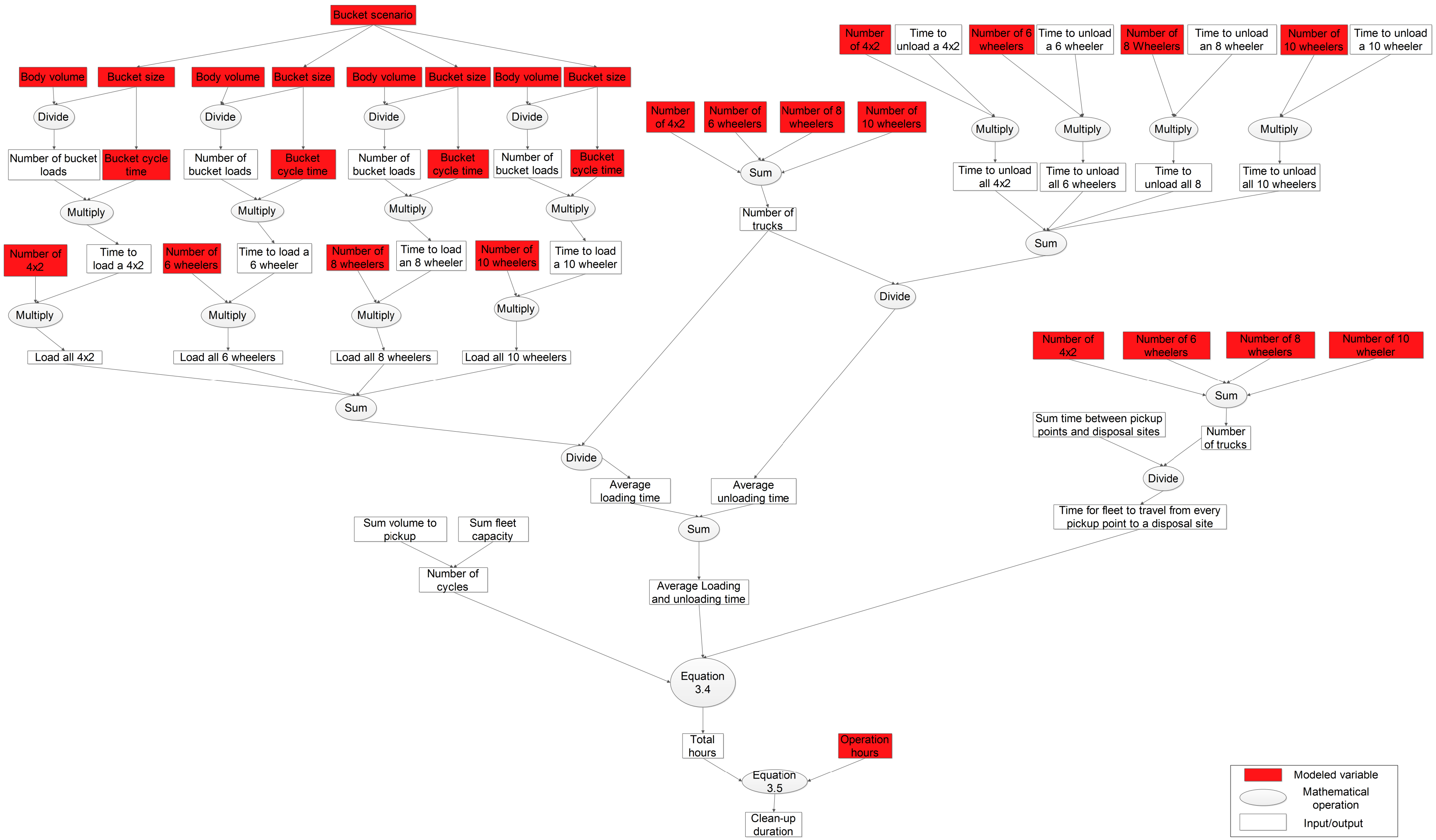


Figure 3.6: Conceptual model of Monte Carlo model for clean-up duration of areas <10 mm thickness

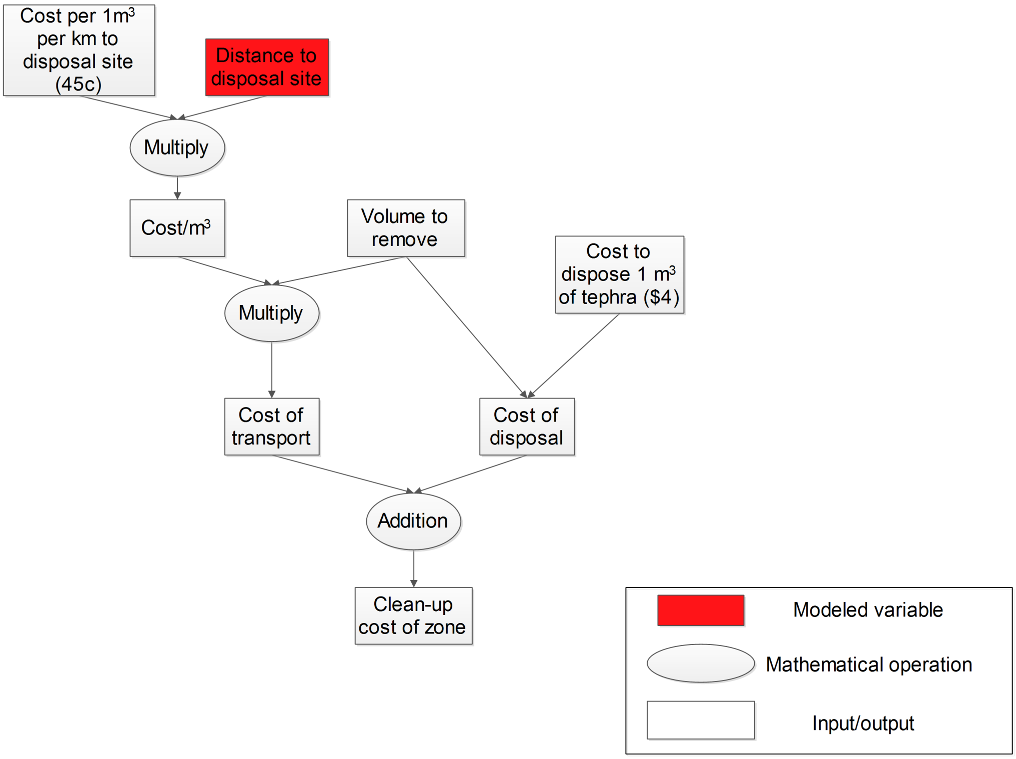


Figure 3.7: Conceptual model of Monte Carlo model for clean-up cost of areas <10 mm thickness

Table 3.2: Parameters for Monte Carlo modelling

	Name	Model	Function	Min	Mean	Max
Category: Sweepers						
	Volume	Duration	RiskIntUniform(5,7)	5	6	7
	Trucks available	Duration	RiskTriang(5,10,20)	5	12	20
	Speed	Duration	RiskTriang(5,6,7)	5	6	7
Category: 4x2						
	Body volume	Duration	RiskIntUniform(7,8)	7	7.5	8
	Trucks available	Duration	RiskTriang(1,50,100)	1	50	100
	Unloading time	Duration	RiskTriang(2,5,10)	2	5.666667	10
Category: 6 wheeler						
	Body volume	Duration	RiskIntUniform(10,20)	10	15	20
	Trucks available	Duration	RiskTriang(1,50,100)	1	50	100
	Unloading time	Duration	RiskTriang(2,5,10)	2	5.666667	10
Category: 8 wheeler						
	Body volume	Duration	RiskIntUniform(19,27)	19	23	27
	Trucks available	Duration	RiskTriang(1,50,100)	1	50	100
	Unloading time	Duration	RiskTriang(2,5,10)	2	5.666667	10
Category: 10 wheeler						
	Body volume	Duration	RiskIntUniform(10,64)	10	37	64
	Trucks available	Duration	RiskTriang(1,50,100)	1	50	100
	Unloading time	Duration	RiskTriang(2,5,10)	2	5.666667	10
Category: Operation Hours						
	Operation hrs	Duration	RiskDiscrete(12,24,0.75,0.25)	12	15	24
Category: Street sweepers						
	km/run	Duration	RiskIntUniform(1,7)	1	4	7
	efficiency factor	Duration	RiskTriang(1,2,10)	1	4.333333	10
	Operation hrs	Duration	RiskDiscrete(12,24,0.75,0.25)	12	15	24

	Name	Model	Function	Min	Mean	Max
Category: Bucket scenario						
	Scenario modelled	Duration	RiskIntUniform(1,4)	1	2.5	4
Category: 1						
	Bucket capacity	Duration	RiskTriang(0.7,1.5,2.3)	0.7	1.5	2.3
	Time	Duration	RiskTriang(27,28,30)	27	28.33333	30
Category: 2						
	Bucket capacity	Duration	RiskTriang(3,3.5,4)	3	3.5	4
	Trucks available	Duration	RiskTriang(30,31.5,33)	30	31.5	33
Category: 3						
	Bucket capacity	Duration	RiskTriang(4.5,5,5.5)	4.5	5	5.5
	Trucks available	Duration	RiskTriang(33,34.5,36)	33	34.5	36
Category: 4						
	Bucket capacity	Duration	RiskIntUniform(10,18)	10	14	18
	Trucks available	Duration	RiskTriang(36,39,42)	36	39	42
Category: Distance to disposal						
	Distance to disposal	Cost	RiskTriang(3,5,20)	3	9.333333	20
Category: Sweeping						
	1mm	Cost	RiskIntUniform(45,90)	$45	$68	$90

3.2.3 Eruption scenarios

Auckland city is exposed to volcanic hazards from both proximal and distant (>50 km) volcanoes. The city is located on the active Auckland Volcanic Field which has produced over 1.7 km^3 of eruptive deposits from 52 monogenetic volcanoes (Kereszturi et al., 2013). Probabilistic hazard modelling suggests that an eruption occurs within the AVF approximately every 1,200 years (Hurst & Smith, 2010). It is also exposed to pyrclastic fall from distant volcanoes to the south, including the Taupo Volcanic Zone, Taranaki volcano and Mayor Island. A probabilistic hazard model indicates return periods for tephra thicknesses of greater than 1 mm, 10 mm from all distal sources are approximately 800 and 3,000 years respectively (Hurst & Smith, 2010). Due to poor preservation potential for thin tephra deposits, these return periods are likely underestimating the recurrence rates. Therefore Auckland city may be impacted by a range of possible tephra deposit spatial extents, volumes and textures from a future volcanic eruption. Overseas experience indicates these factors can independently and collectively influence clean-up methods, duration and cost (Chapter 2). This sub-section reviews proximal and distal volcanic hazards for Auckland city, and then describes and justifies the selection of a range of eruption scenarios used to assess tephra deposit clean-up impact in Auckland.

3.2.3.1 Distal scenarios

The North Island of New Zealand has a number of volcanoes which can produce tephra fall which impact Auckland. Lake cores from within Auckland have identified 70 distal tephra fall deposits ranging from 0.5-630 mm(Green et al., 2014). Rhyolitic tephra deposit have been identified as sourced from Taupo (TVC), Okataina (OVC) and Mayor Island (MI) volcanoes; while andesitic tephras have been identified from Mt. Taranaki (Tk) and Mt. Tongariro/Ruapehu (TgVc) (Green et al., 2014). Auckland is most regularly impacted by tephra fall from Mt. Taranaki with tephra thickness of 1-10 mm (Table 3.3).

This thesis considers two distal scenarios for clean-up impact modelling purposes: (1) thin distal tephra fall (1 mm), and (2) thick distal tephra fall (10 mm). These two scenarios were chosen to test the model under different methods of clean-up (i.e. (1) street sweeping operation, (2) heavy machinery and dump truck operation). A thin distal scenario is one which could be similar to previous Mt. Taranaki eruptions where tephra fall has been deposited in Auckland. A thick distal scenario could be similar to an eruption at TVC or OVC. It is accepted that there will be localised thickening due to topography, however, in the interests of simplicity it is assumed that fall deposits will be uniformly distributed across the Auckland Metropolitan area.

Table 3.3: Distal tephra recurrence intervals and approximate range of thickness (Molloy et al., 2009)

Volcano	Recurrence interval (k.y)	Thickness (mm)
Taranaki	1.5	1-10
Taupo Volcanic Zone	3.8	2-20
Tongariro	11.4	1
Mayor Island	40	2-20

Exposure of Auckland's urban environment for distal eruption scenarios are summarised in Table 3.4. All of metropolitan Auckland will be impacted by such an event, with over 1,200,000 people and 411,000 private dwellings affected. For a thin distal scenario, impact will mainly be as a result of road network disruption and airport closure. Traffic restrictions will need to be put in place until roads can be cleaned. A thick distal scenario will be much more problematic due to pyroclastics deposits needing removal from roads and private properties.

Table 3.4: Exposure of urban environment due to distal eruption scenarios. Population and dwellings data from 2013 Census (Statistics New Zealand, 2014c)

Scenario	Population	Road lanes (km)	Dwellings	Total volume (m^3)
1 mm	1,248,699	10,664	411,417	808,342
10 mm	1,248,699	10,664	411,417	8,083,419

3.2.3.2 Proximal Scenarios

This thesis takes two proximal eruption scenarios, one developed for Auckland Regional Council in 1997 (Johnston et al., 1997), and the other based on a Three Kings eruption. Eruptions within the AVF can occur anywhere within the metropolitan area (and offshore) and depending on water availability can influence eruption type (wet explosive or dry magmatic) (Kereszturi et al., 2014). Scenarios were selected for the purpose of capturing a range on potential eruption impacts. Minimum eruptive volumes of volcanoes in Auckland Volcanic Field range from 75,000 m^3 (Ash Hill) to 699,000,000 m^3 (Rangitoto) with a median eruptive volume of 7,200,000 m^3 (Kohuora) (Kereszturi et al., 2013). However, these volumes do not include tephra fall volumes and should be considered as minima (Kereszturi et al., 2013).

3.2.3.3 Tamaki Estuary proximal scenario

Tamaki Estuary eruption scenario is based on scenario developed by Johnston et al. (1997) (Figure 3.8). It consists of an initially small eruption, with explosions ejecting lithics, and rapidly increasing in explosivity. A 10-12 km eruption column leads to an eruption cloud dispersing wet tephra fall northwards. Ballistic clasts are ejected out to 1.6 km from the vent with some reaching residential areas. Base surges initially impact only coastal areas within 1 km from vent. Larger and faster moving surges then override these surges and travel radially out to 2 km. Surges eventually travel radially out to 3 km with thicknesses greater than 30 cm, resulting in a total of 8,600,000 m^3 of surge deposits. Following explosive eruptions, magmatic eruptions continue for several weeks, which build a small scoria cone in the crater. Very little tephra is ejected during this phase. The total eruptive volume (including tephra fall) of this eruption is approximately 11,000,000 m^3 which would make it slightly larger than the median sized eruptions in the AVF reported by Kereszturi et al. (2013).

Exposure of urban environment are summarised in Table 3.5. This scenario will impact on over 300,000 people. Most will only be impacted by thin tephra fall (1-10 mm). However, an evacuation zone of 5 km radius around the vent (consistent with Auckland Volcanic Field Contingency Plan) will result in about 140,000 people being evacuated. A total of over 2,400 km of road lanes will be at reduced functionality until material is removed. Under this scenario, it is unlikely any private dwellings will be at risk of roof collapse due to tephra fall thicknesses not exceeding 200 mm (Jenkins et al. 2014a). However, over 18,000 private dwellings will be impacted by surges of varying intensity which could result in highly damaged property within 3 km of the vent.

Table 3.5: Summary of exposure for Tamaki Estuary eruption scenario. Population and dwellings data from 2013 Census (Statistics New Zealand, 2014c)

Zone	Population	Road lanes (km)	Dwellings	volume on land (m^3)
1-10 mm	141,135	1,309	45,993	920,630
>1 cm	20,751	65	7,800	1,177,894
Evac - fall	83,778	650	29,697	619,841
Evac - surge	56,388	431	18,372	8,666,511
Total	**302,052**	**2,455**	**101,862**	**11,384,876**

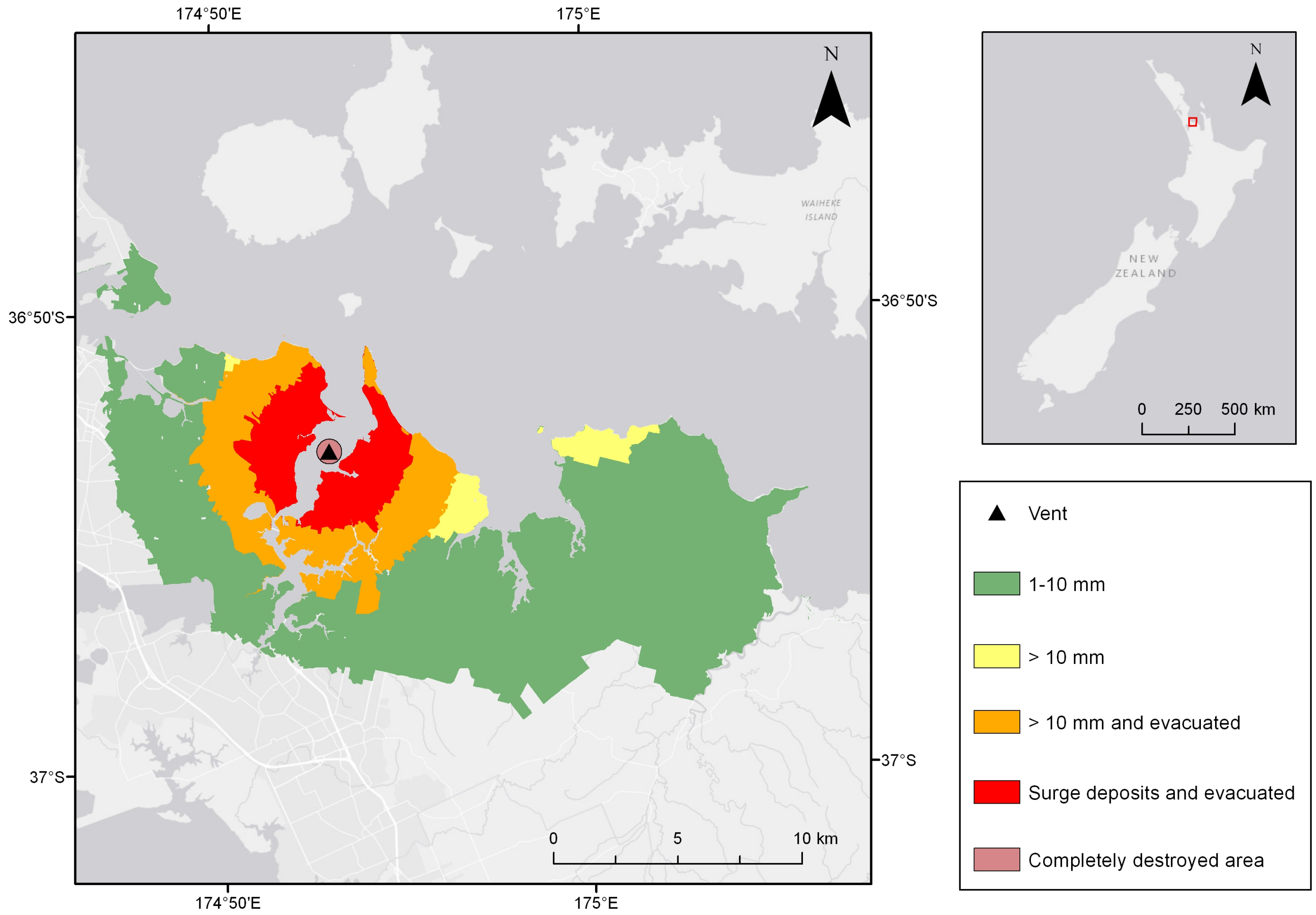


Figure 3.8: Tamaki Estuary eruption scenario

3.2.3.4 Three Kings proximal scenario

Three Kings volcano in the AVF erupted approximately 28.5 ka with an initial explosive phreatomagmatic phase changing into a dry fire fountaining phase as water supply diminished (Hayward et al. 2011). Despite much of Three Kings eruption deposits having been quarried or beneath suburban neighbourhoods, making event reconstruction difficult, Hayward et al. (2011) suggest the initial phreatomagmatic phase created a massive explosion crater about 800 m across and 200 m deep. A number of different vents within the crater began fire fountaining following the initial explosive phase, partially filling the crater and building scoria cones up to 45 m high. Lapilli tephra was blown northeast for several kilometres and built up thicknesses in excess of 3 m at One Tree Hill (2.5 km from vent)(Hayward et al., 2011), and 1 m at Greenlane (4 km from vent) (Kermode, 1992). Lava flows filled in many depressions between scoria cones. Lava flows breached the tuff ring and flowed about 3 km down a valley towards Western Springs. Total eruptive volume (not including tephra fall) is 0.69 km^3 (Kereszturi et al., 2013) making it the second largest magnitude eruption in the Auckland Volcanic Field. As such, it should be considered as an upper bound on a potential future eruption, which is why this study used it for assessing potential impact of tephra clean-up in Auckland.

Currently, there is no published data on tephra fall dispersion from the Three Kings eruption. For this reason isopachs from the Tamaki Estuary eruption scenario are used to estimate tephra fall dispersion across the metropolitan Auckland area, along with the extent of mapped tephra deposits from Kermode (1992) (Figure 3.9). Taking this approach will result in an under estimation of tephra fall and pyroclastic flow volumes.

Three Kings eruption scenario will be much more disruptive and damaging on the urban environment than the Tamaki Estuary scenario (Table 3.6). This eruption scenario will result in over 46,000,000 m^3 of tephra being deposited on land, much of it from base surge and fire-fountaining. In total, over 900,000 people will be impacted by this event, although half will only be impacted by tephra fall of 1-10 mm and over 200,000 people will require evacuation from within 5 km of the eruptive vent. Auckland's road network is likely to be severely disrupted with over 7,000 km of road lanes, including the motorway system at reduced functionality and requiring clean-up. Over 150,000 private dwellings will be affected by tephra fall of >10 mm and are likely to require assistance from municipal authorities to remove.

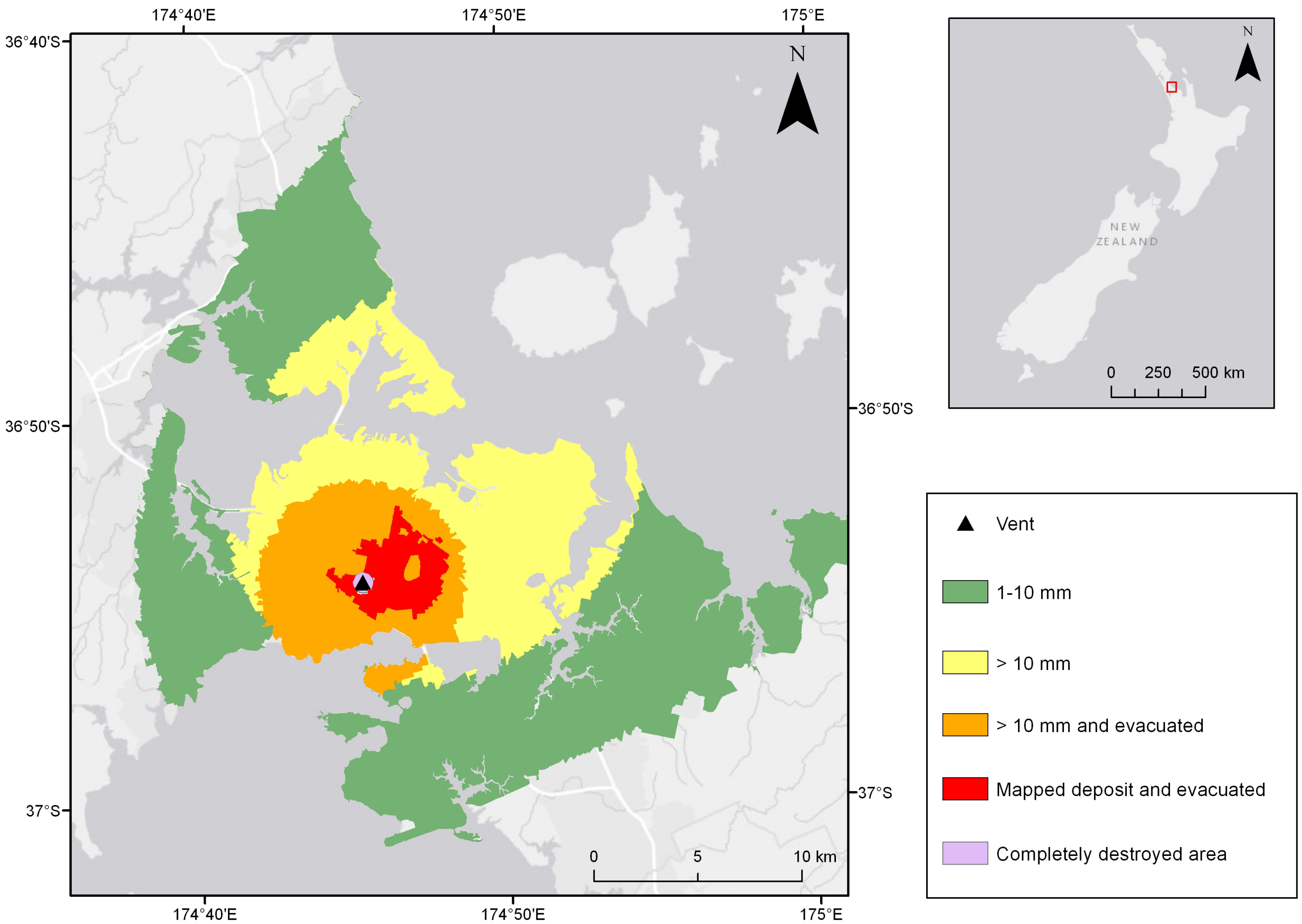


Figure 3.9: Map of Three Kings eruption scenario

Table 3.6: Summary of exposure for Three Kings eruption scenario. Population and dwellings data from 2013 Census (Statistics New Zealand, 2014c)

Zone	Population	Road lanes (km)	Dwellings	Total volume (m^3)
1-10 mm	456,516	3,392	143,793	1,489,962
>1 cm	266,685	2,228	98,634	3,293,051
Evac - fall	157,977	1,208	53,733	2,398,835
Evac - surge	47,208	311	15,903	39,070,225
Total	**927,386**	**7139**	**312,603**	**46,252,073**

3.3 Results

This section presents results from geospatial clean-up impact modelling of different eruption scenarios for Auckland. The section considers distal and proximal clean-up operations separately. First, results of potential clean-up removal volumes, duration, and costs. Then, a simple benefit-cost analysis is undertaken to demonstrate whether clean-up in each zone is economically viable.

3.3.1 Removal volumes

The total volume of tephra fall and pyroclastic flow deposits estimated to require removal based on the conceptual framework established in Section 2 are presented in Table 3.7. Adjusting these values to consider area impacted shows how the values compare with case study cities from Chapter Two (Figure 3.10).

Table 3.7: Total volumes to be removed under optimised clean-up for eruption scenarios

Scenario	Optimised removal volume (m3)
Thin distal	36,205
Thick distal	2,616,784
Tamaki Estuary	7,773,845
Three Kings	25,798,160

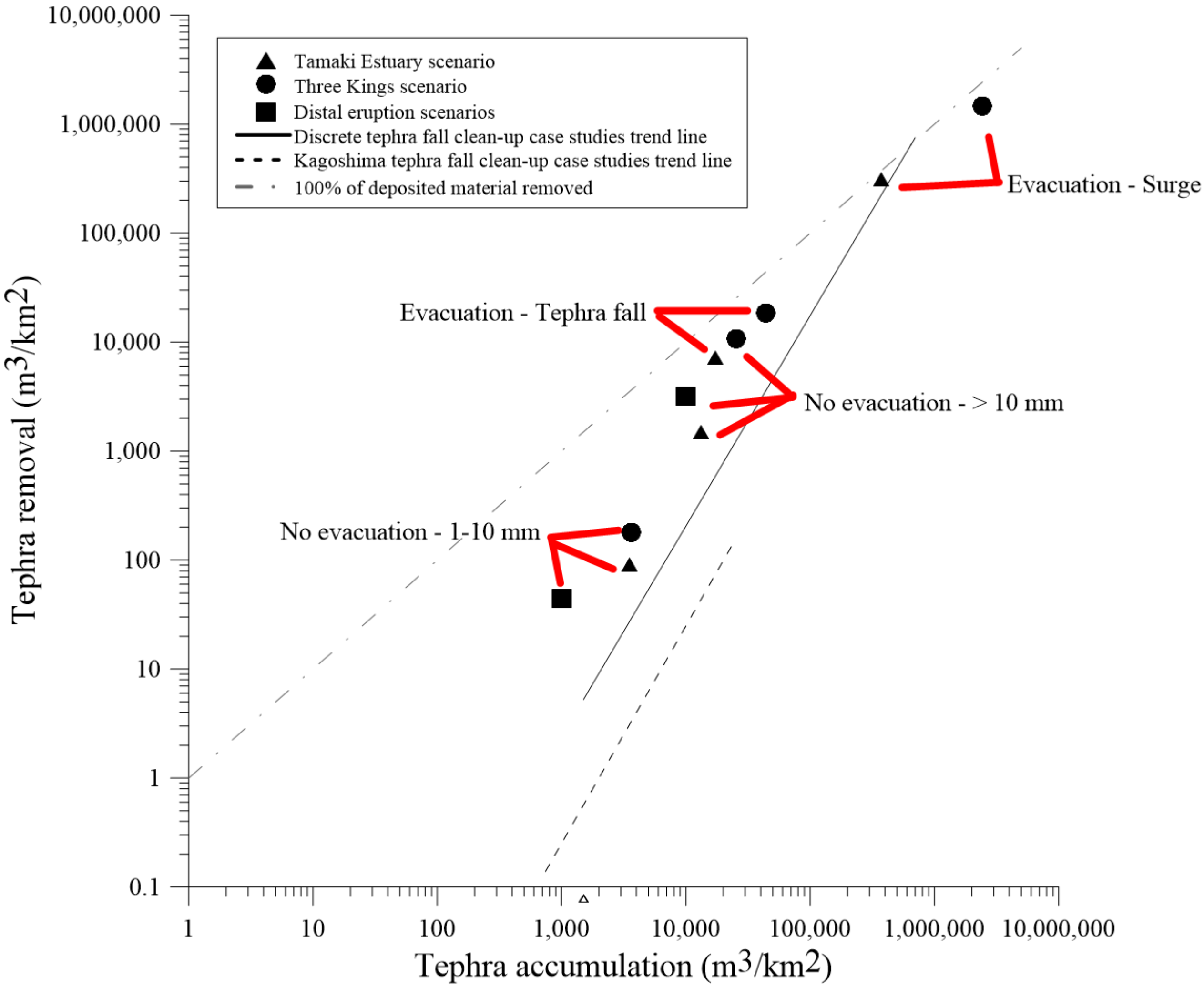


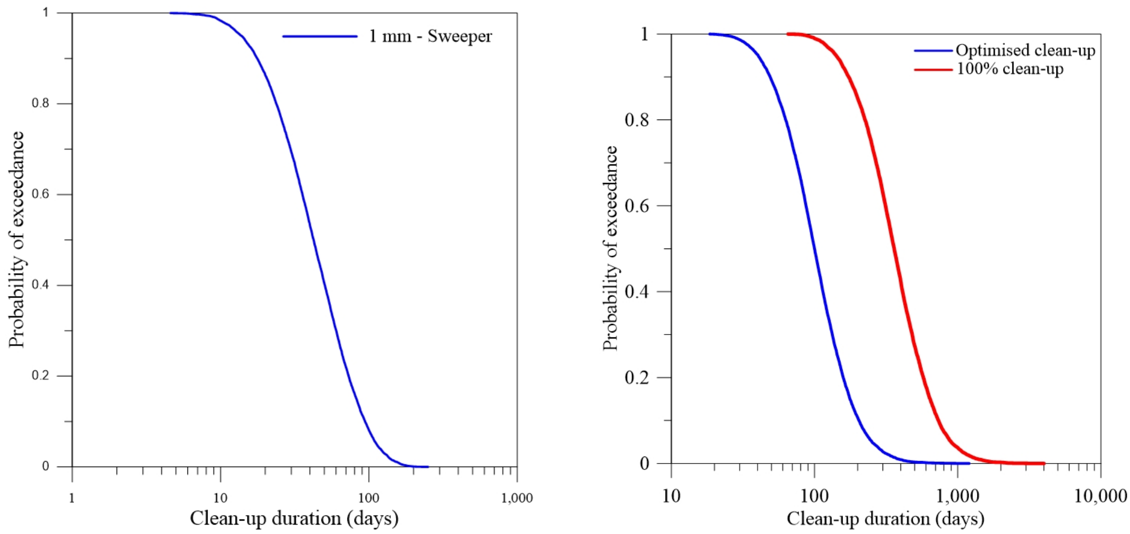
Figure 3.10: Clean-up efficiency of proximal eruption scenarios

3.3.2 Clean-up impact

Monte Carlo modelling results indicating cost and duration of clean-up operations are presented in the sections below. First, results from distal eruption scenarios are presented, followed by proximal eruption scenarios.

3.3.2.1 Distal eruption scenarios

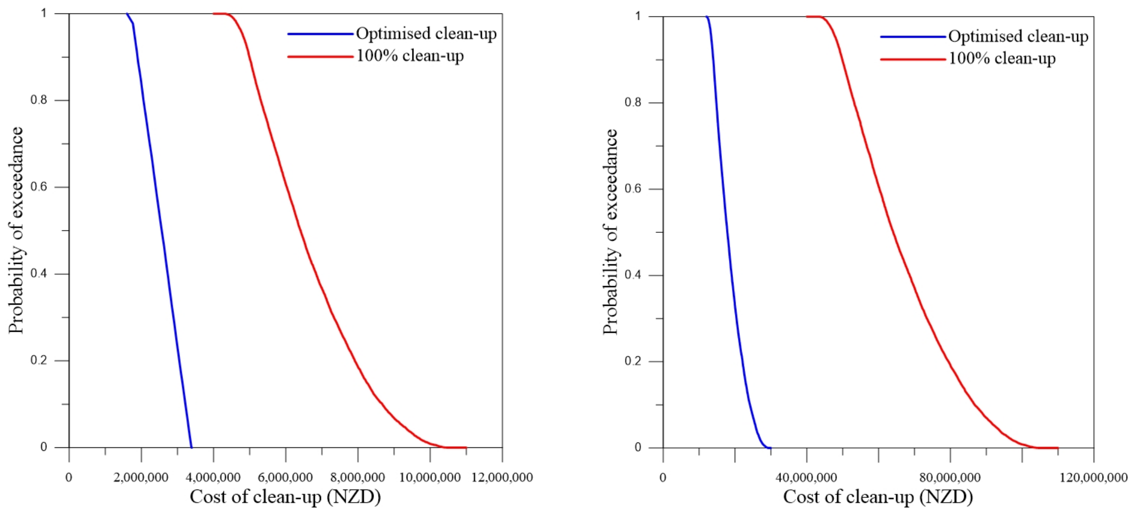
The model suggests that both distal eruption scenarios are likely to have clean-up operations in excess of 1 week (Figure 3.11). For the thin distal scenario, there is an 90% probability that optimised clean-up will exceed 1 month and 10% probability that clean-up will exceed 3 months. For the thick distal scenario there is 90% probability that clean-up will exceed 50 days and greater than 10% probability of exceeding 6 months.



(a) 1 mm distal scenario (b) 10 mm distal scenario

Figure 3.11: Probability of exceedance curves for clean-up duration of distal clean-up scenarios

Clean-up cost modelling results indicate that clean-up of distal eruption scenarios is likely to exceed NZ$ 2 million (Figure 3.12). For the thin distal scenario, there is 90% probability that optimised clean-up will exceed NZ$2 million and greater than 10% probability that clean-up cost will exceed NZ$ 3 million. For the thick distal scenario there is 90% probability that clean-up will exceed NZ$ 15 million and greater than 10% probability of exceeding NZ$ 25 million.



(a) 1 mm distal scenario (b) 10 mm distal scenario

Figure 3.12: Probability of exceedance curves for clean-up cost of distal clean-up scenarios

3.3.2.2 Proximal eruption scenarios

Probability of exceedance curves for clean-up duration of proximal scenarios are presented in Figure 3.13. For the Tamaki Estuary eruption scenario, the model suggests there is 90% probability that optimised clean-up of areas impacted by tephra fall of 1-10 mm will exceed 40 days and 10% probability of exceeding 6 months. Areas outside the evacuation zone impacted by tephra fall of >10 mm have 90% probability of exceeding 2 days and 10% probability of exceeding 1 week. Within the evacuation zone, cleaning areas not impacted by surge have 90% probability of exceeding 3 days and 10% probability of exceeding 20 days. The surge deposits will take a long time to clean-up, with greater than 90% probability of exceeding 2.5 months and greater than 10% probability of exceeding 6 months.

For the Three Kings eruption scenario, there is greater than 90% probability that optimised clean-up of areas impacted by tephra fall of 1-10 mm will exceed 2.5 months. Areas outside the evacuation zone impacted by tephra fall of >10 mm have 90% probability of exceeding about 1 month and greater than 10% probability of exceeding 100 days. Within the evacuation zone, cleaning areas not within the area occupied by the mapped deposit have greater than 90% probability of exceeding 1 week and greater than 10% probability of exceeding 1 month. The mapped deposit will take a very long time to clean-up, with greater than 90% probability of exceeding 6 months and greater than 10% probability of exceeding 2 years.

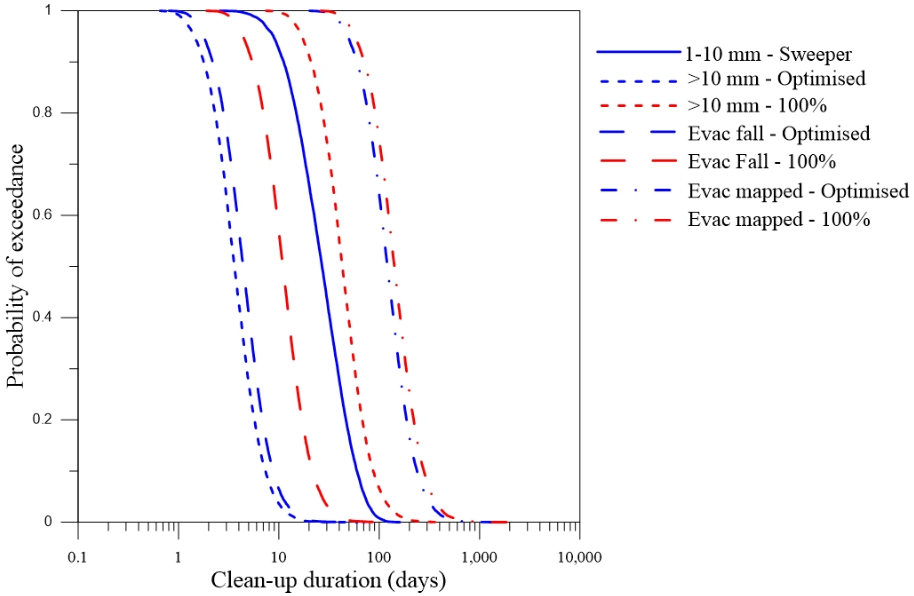
Probability of exceedance graphs detailing clean-up cost for different zones are presented in Figure 3.14. For the Tamaki Estuary eruption scenario, it is almost certain that optimised clean-up of areas impacted by tephra fall of 1-10 mm will cost approximately NZ$200,000. Areas outside the evacuation zone impacted by tephra fall of >10 mm have 90% probability of exceeding NZ$600,000 and 10% probability of exceeding NZ$1 million. Within the evacuation zone, cleaning areas not impacted by surge have more than 90% probability of costing more than NZ$1 million and 10% probability of exceeding NZ$2.5 million. The surge deposits will be very costly to remove, with greater than 90% probability of exceeding NZ$50 million and greater than 10% probability of exceeding NZ$80 million.

For the Three kings eruption scenario, results indicate that optimised clean-up of areas impacted by tephra fall of 1-10 mm will exceed NZ$500,000. Areas outside the evacuation zone impacted by tephra fall of >10 mm have 90% probability of exceeding NZ$10 million and greater than 10% probability of exceeding NZ$15 million. Within the evacuation zone, cleaning areas not impacted by surge have 90% probability of costing more than NZ$6 million and more than 10% probability of exceeding NZ$10 million. The surge deposits will be extremely costly to remove, with a greater than 90% probability of exceeding NZ$200 million and greater than 10% probability of exceeding NZ$250 million.

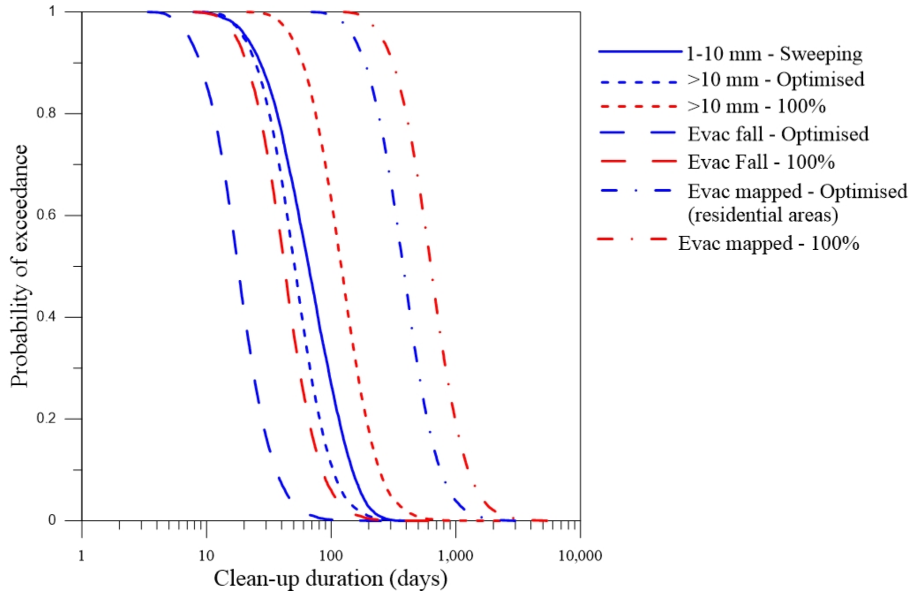
3.3.3 Benefit-cost analysis of proximal clean-up

Results from a benefit-cost analysis for proximal clean-up are presented in Figures 3.15 and 3.16. In this simplified analysis, it will be economically viable to clean-up all areas in the Tamaki eruption scenario due to benefit-cost ratios between 100-3,000 for removing tephra fall. Even in surge impacted areas it is almost certain that a benefit-cost ratio of cleaning up these areas exceeds 4.

Similar results are seen for tephra fall impacted areas in the Three Kings eruption scenario. This analysis suggests that residential areas within the mapped deposit extent will be economically viable to clean-up up. However, cleaning up 100% of the mapped deposit results in a 50% probability of benefit-cost being less than 1, suggesting clean-up of 100% of the mapped deposit is unlikely to be economically viable to clean-up.

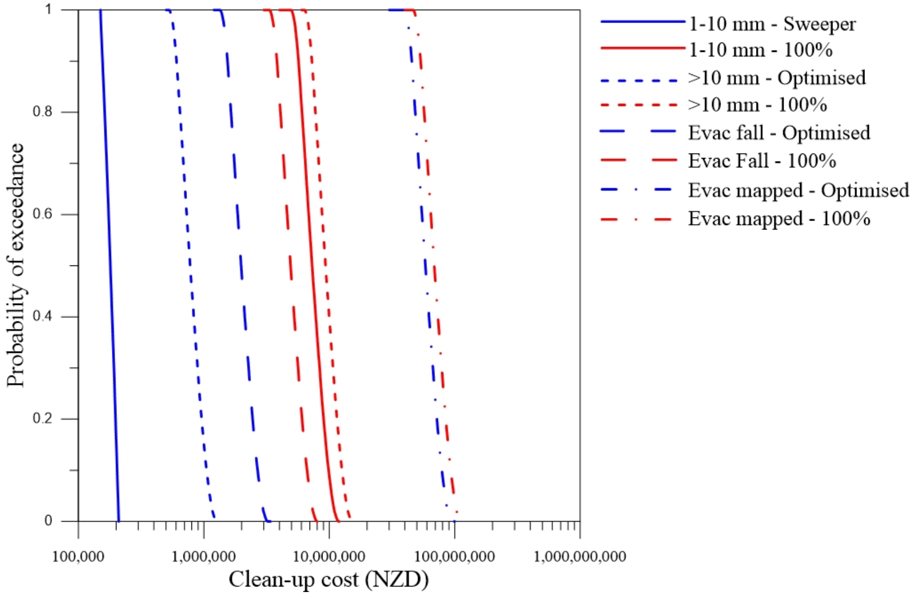


(a) Tamaki Estuary eruption scenario

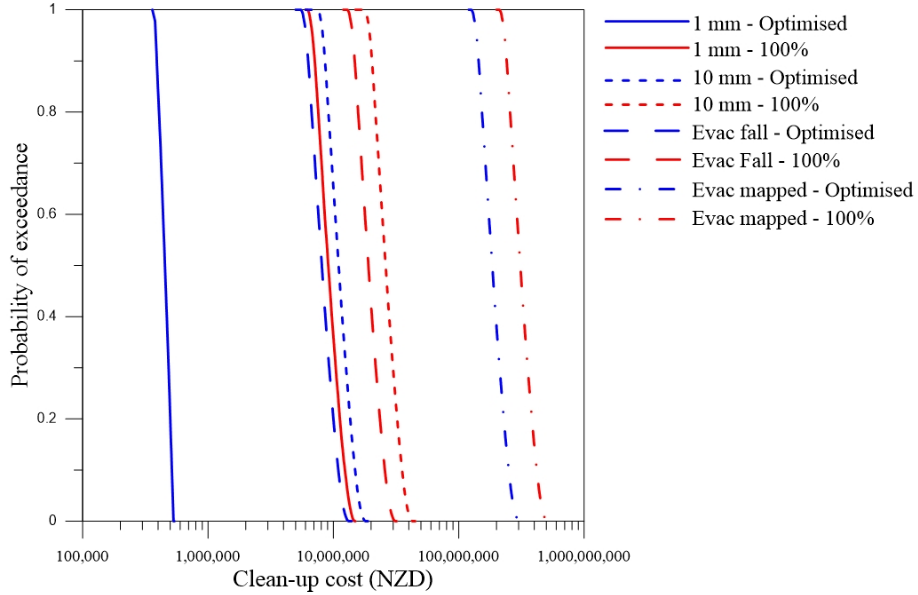


(b) Three Kings eruption scenario

Figure 3.13: Probability of exceedance curves for clean-up duration of zones for proximal eruption scenarios

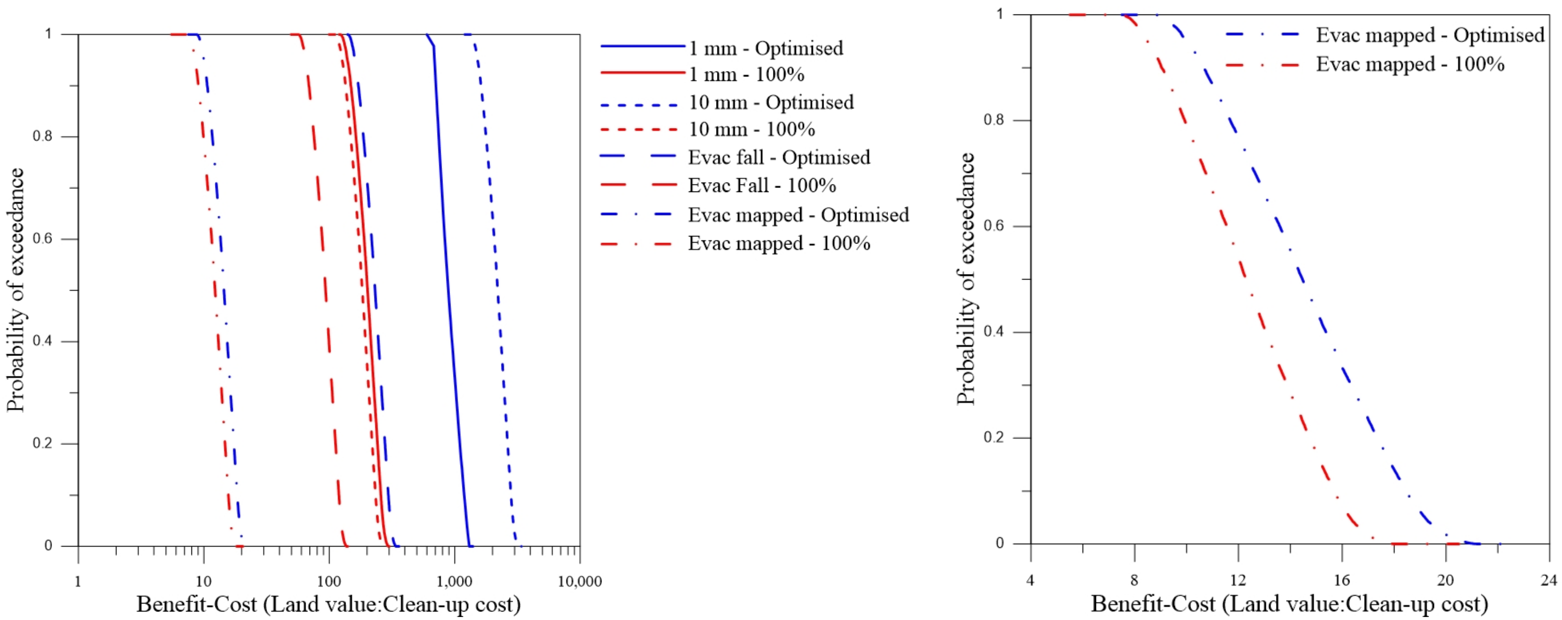


(a) Tamaki Estuary eruption scenario



(b) Three Kings eruption scenario

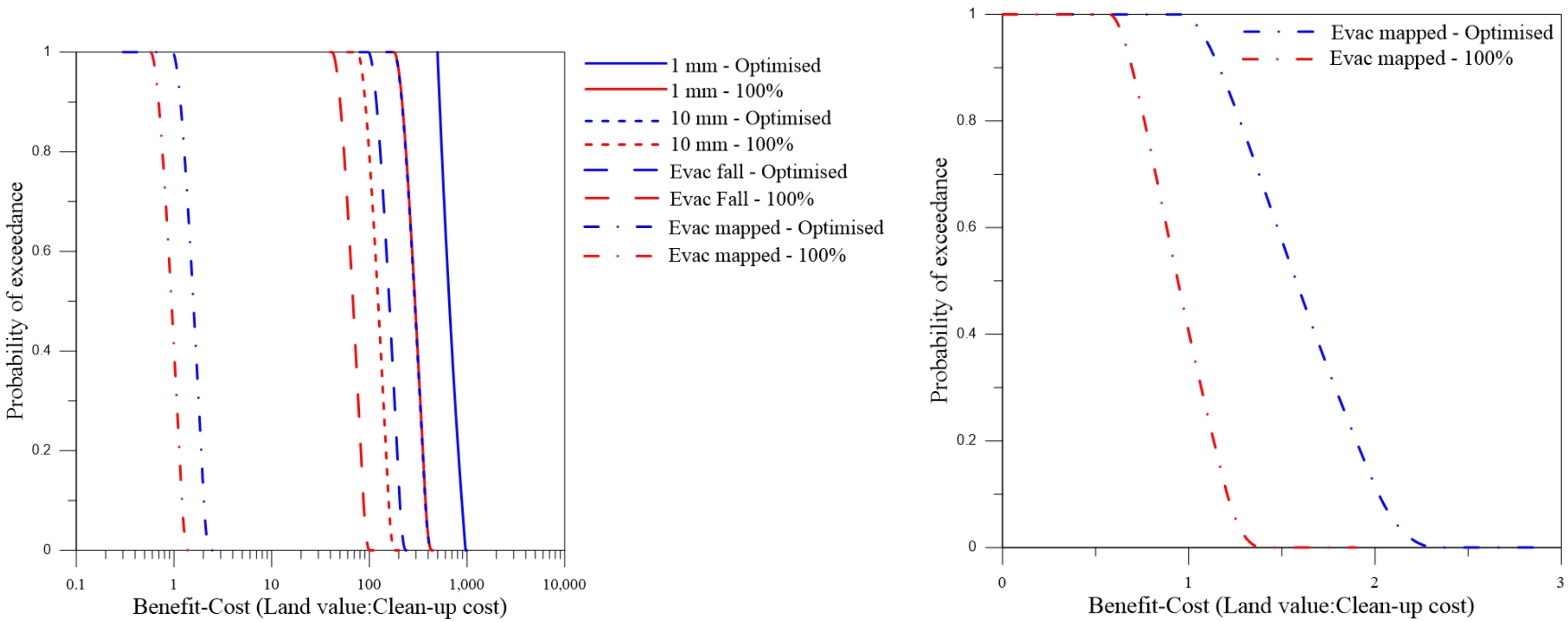
Figure 3.14: Probability of exceedance curves for clean-up cost of zones for proximal eruption scenarios



(a) All zones

(b) Surge zone only

Figure 3.15: Probability of exceedance curves for benefit:cost of cleaning up Tamaki Estuary tephra deposits



(a) All zones

(b) Surge zone only

Figure 3.16: Probability of exceedance curves for benefit:cost of cleaning up Three Kings tephra deposits

3.3.4 Model sensitivity

It is important to understand the sensitivity of the clean-up model to model parameters in order to identify model parameters which are introducing uncertainty within the model. Identification of model parameters introducing large uncertainty to the model can assist with understanding how to refine the model and to assess model robustness. This subsection provides results from a sensitivity analysis of the model parameters and identifies those which have the greatest influence on model results.

3.3.4.1 Clean-up duration

The street sweeping clean-up duration model is most sensitive to efficiency of the street sweeper truck at picking up tephra. This is because as a sweepers efficiency at picking up tephra decreases it will be required to complete more cycles to remove the same volume of material. The model is also sensitive to the number of sweeper trucks which are operational. This is not surprising because if there are more sweeper trucks operating at the same time, a greater volume of material can be picked up in a shorter span of time.

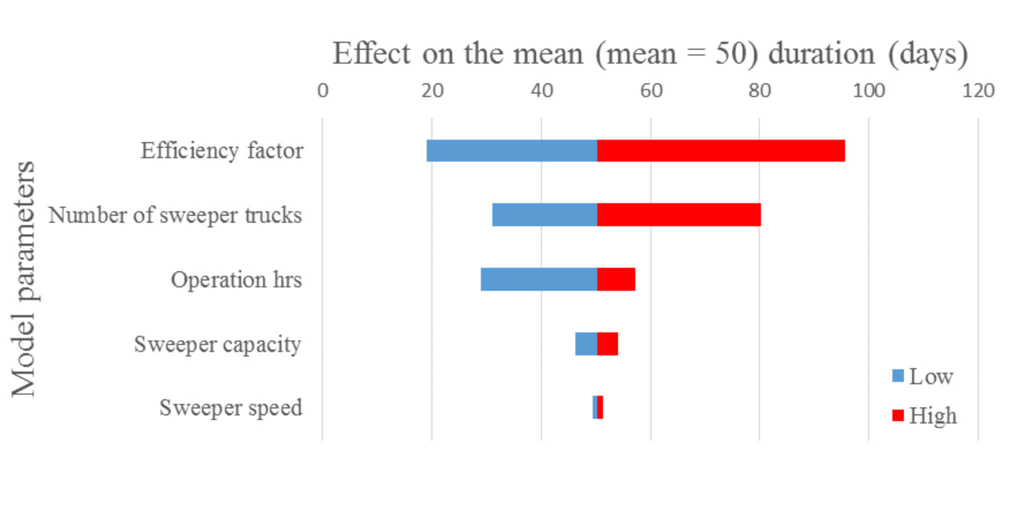


Figure 3.17: Sensitivity of street sweeping clean-up duration model to equation parameters (1 mm distal scenario)

The dump truck clean-up duration model is heavily influenced by the number of trucks that are available, especially the dump trucks which can carry larger volumes. This is because they reduce the number of trips which need to be completed to remove the required volume of tephra. The model is also sensitive to the hours per day that trucks can travel to and from disposal sites.

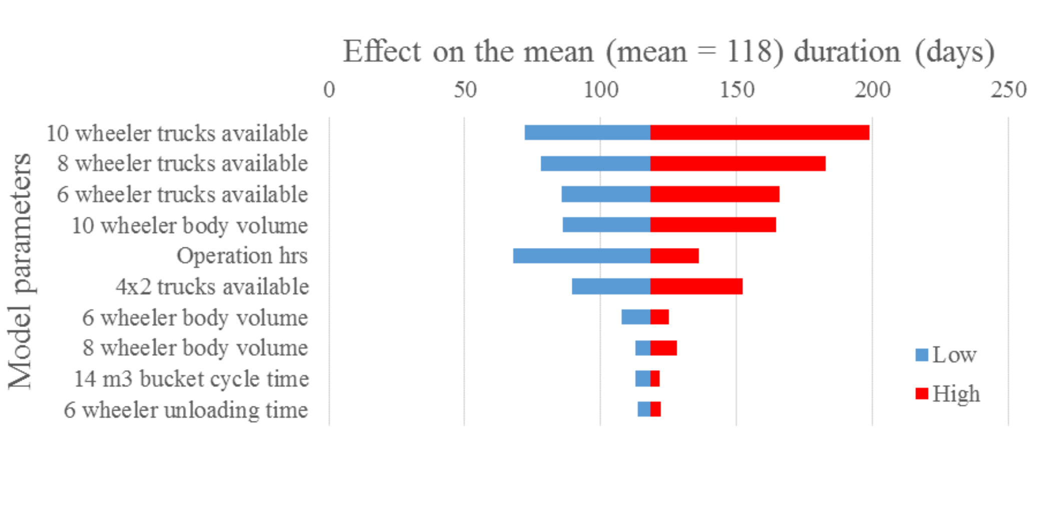


Figure 3.18: Sensitivity of dump truck clean-up duration model to equation parameters (10 mm distal scenario)

3.3.4.2 Clean-up cost

The cost model is much simpler than the duration models and for this reason are only sensitive to either the cost per kilometre (street sweeping operation) or the distance that dump trucks have to travel to disposal sites.

3.4 Discussion

The results from clean-up impact modelling indicate that even under ideal conditions, clean-up of tephra in Auckland following a proximal or distal volcanic eruption is likely to be expensive and time consuming. This section first critically discusses the results from geospatial impact modelling followed by discussing implications of these results on clean-up operation planning for Auckland.

3.4.1 Discussion of results

This subsection critically discusses results of clean-up impact modelling. First, a summary of model assumptions and limitations is discussed. Next, discussion of estimated removal volumes and comparisons with previous tephra fall clean-up operations is presented. Following this is a discussion regarding clean-up duration with the purpose of discussing complexity and limitations within the model. Next, discussion towards costs of clean-up operations and potential sources of cost not considered within the model. A discussion of results from benefit-cost analysis of clean-up in different zones is then discussed. Finally areas of model refinement and potential applications of the model are discussed.

3.4.1.1 Clean-up model assumptions and limitations

A number of assumptions and limitations exist within components of the clean-up model which could have an influence on model results (Table 3.8). Assumptions and limitations have been categorised as to whether they would result in the model output being over-estimated, under-estimated, or likely negligible impact on model results. Table 3.8 suggests the model is likely under-estimating the duration and cost of clean-up. A potentially important influence on under-estimation is that the impact of traffic on hauling time is not included within the model. Reductions in visibility and traction have previously resulted in reduced speed limits or closed roads (Blong, 1984; Wilson et al. 2012; Wilson et al. 2014), and so hauling times are likely to be optimistic. A further significant influence on the speed of clean-up will be disposal site operational capacity (truck visits per day) due to bottlenecks or resource consents. There is a possibility that there will be restrictions placed on the operational hours disposal sites can be open for as most are located in residential areas.

Table 3.8: Assumptions and limitations of the clean-up model

Assumption/limitation	Implication for model		
	Under estimation	Over estimation	Negligible
Removal volumes model			
No other waste streams (e.g. construction/demolition)	■		
No clean-up within 800 m of vent due to destruction	■		
No remobilisation	■		
No pyroclastic deposits infiltrating storm water system		■	
100% of pyroclastic material on surfaces is cleaned		■	
No ongoing pyroclastic falls (> 6 months)		■	
No consideration of asset sub categories on quality of clean-up		■	
No consideration of vegetation clean-up	■		
Clean-up duration model			
Clean-up vehicles can operation on roads covered with pyroclastic deposits	■		
No traffic	■		
Time to move material from properties to pick-up points			■
No restrictions on truck routes to disposal sites	■		
Worker breaks and vehicle maintenance	■		
Closest of contingency plan disposal sites are used	■		
Duration for scoping and planning			■
Disposal site operational capacity not considered	■		
Street sweeper travel inefficiencies	■		
Rational operators within system	■		
Resources (loaders, labourers, graders) will be scaled to meet truck fleet requirements	■		
Experience level of clean-up managers not considered	■		
Remobilisation not considered	■		
Rainfall not considered	■	■	
Time it takes material to accumulate not considered	■		
Clean-up cost model			
No direct costs other than transportation and disposal considered	■		
No post-disaster price escalation	■		
Business disruption costs not considered	■		

3.4.1.2 Removal volumes

Removal estimates based on using the conceptual framework outlined earlier in this chapter(Figure 3.2) are higher than the trendline of discrete tephra fall clean-up from Figure 3.10. These estimates are probably within an acceptable range due to: (1) Auckland being highly developed (lots of impervious surfaces) compared to some of the case study cities in Chapter 2 meaning a greater area taken up with roads, roofs, and impervious surfaces, (2) Auckland is likely to have a low tolerance to dust as a result of suspension of fine tephra particles in the air due to strict air pollution regulations, and (3) some variability already within the case study data.

Thoroughness of clean-up (percentage of material removed from a surface) is an important consideration, as some areas could be cleaned to a higher quality than others (e.g. Central Business District compared to residential areas). In this research it has been assumed that every surface that requires cleaning has 100% of the material removed from it. However, it is possible that not all material can or will be removed from the surface. This could occur due to fine grained material getting suck within pores of concrete (e.g. Portland - St Helens 1980), difficult to reach areas (Figure 3.19), or some material might end up being washed into storm water drains by rain or during clean-up (e.g. Catania - Etna 2002). There has also been instances where individuals have not cleaned up material and this is particularly problematic in areas of high absentee ownership such as rental properties (Kartez et al., 1980). Further, the model assumes that clean-up occurs after all material has been deposited. However, it is possible that multiple eruptions could occur and that clean-up will be conducted to a lower quality or delayed (Sword-Daniels et al., 2014). There has been no consideration of asset sub categories (e.g. road surface type or building type) on removal estimates. For example, removal of material from gravel road surfaces could require significant volumes of road surface gravel to be removed along with tephra deposits, which would result in the model underestimating the total volume. However, the study area is confined to metropolitan Auckland and so the number of these roads are very minimal. All buildings with an area of 30 m^2 are treated equal within the model. This could result in an overestimation of the total volume removed as some low value buildings (e.g. sheds) might not be always be cleaned up. If clean-up response expands to include private property clean-up there is potential for individuals to want all material on a property to be removed as part of the coordinated clean-up effort. This would influence the model by underestimating the total volume of material being removed.

Figure 3.19: Fine grained tephra fall within inhomogeneous surfaces in Yogyakarta about 7 months following February 2014 Mt. Kelud eruption

3.4.1.3 Clean-up duration

A number of factors can influence the model results for clean-up duration:

- kilometres of road needing clean-up;
- volume of material requiring disposal;
- number of street sweepers available for use;
- efficiency of those street sweepers to remove fine grained pryoclastic deposits;
- volumetric capacity of the street sweepers;
- hours per day of spent on street sweeping.

The most important aspect influencing clean-up of thin deposits using street sweepers is the efficiency that they can pick up tephra. Street sweepers often also have to operate within traffic and manoeuvre between parked vehicles which ultimately slows the speed with which they can clean tephra deposits from road surfaces (Clark & Lee, 1965). Additionally, they will have to return to disposal sites or depots to empty loads, for scheduled maintenance, and worker breaks. As such, these inefficiencies will increase the time it takes to clean-up road surfaces.

Auckland Council contracts out much of the street sweeping work for the city and how many street sweepers would be available is unknown, however there were 12 street sweepers on standby following the 1995 eruption of Mt. Ruapehu (Roy Robertson pers comm, 2014). However, in the situation of a distal eruption, Auckland Council may elect to lend sweepers out to other areas which have also been impacted, or might have street sweepers on loan from less effected areas.

For thick distal scenarios (10 mm), clean-up is likely to last between 2 to 6 months. This is largely due to the wide scale of impact across the entire Auckland metropolitan area and assistance needing to be provided to private property owners to dispose of tephra fall. Factors that influence model results are:

- volume of material to be removed;
- resource availability (number of trucks, loaders, workforce);
- disposal site location;
- operational capacity (number of trucks per day and total volumetric capacity);
- hours per day of operation.

Although the model is most sensitive to truck resource availability, operational capacity at disposal sites is likely to be a controlling factor towards how many trucks can be used. This is because having too many trucks for the operational capacity of disposal sites will mean that trucks spend too much time queuing to enter disposal sites. Operational capacity was not considered as part of the model because of a lack of detailed information regarding disposal sites.

It is challenging to determine a total clean-up duration for proximal eruption because due to varying levels of impact, multiple methods of clean-up will be required in different areas. It is assumed in this analysis that each zone is treated as a separate clean-up operation, and each zone has access to the full inventory of resources. This means that the 1-10 mm zone will utilise all the street sweepers until it is cleaned, and the >10 mm zone utilises all the trucks and loaders available until complete. However, areas inside an evacuation zone will also need heavy machinery and dump trucks to remove tephra, but evacuation time is unknown. It could be that evacuation is prolonged in which case the outer lying areas could be mostly cleaned up before people re-enter and clean-up evacuated areas. Conversely evacuation could be short lived, at which time clean-up of outer lying areas might not be complete, meaning that resources become spread over a larger area.

3.4.1.4 Clean-up cost

As demand for a quick clean-up operation increases, there will be a bottleneck on resource availability. Auckland Council have agreements with contractors to provide services for the council in a disaster environment (Richard Woods, pers comm 2014). Although the exact conditions of these contracts are confidential, it is assumed in this research that limits will be put on the level of price escalation that occurs. There is no strong evidence to suggest price escalation occurs within disaster waste management process (Brown, 2012). Clean-up costs cited in this thesis are designed to assess the transportation and disposal of tephra related to coordinated clean-up operations overseen by the Auckland Council. The costs associated with cleaning properties (e.g. labour costs) have not been considered. Also not considered in this work is that there is likely to be increased demand for private contractors to assist residential and business owners with clean-up of properties. Resources for such services could be limited because of the need to assist with municipal clean-up activities. Although, it is also likely that a significant volunteer effort will be initiated, as seen in Christchurch following the 2010-2011 earthquakes (Villemure, 2013) which offsets the total cost of clean-up to individuals due to free labour.

3.4.1.5 Benefit-cost of clean-up

The benefit-cost analysis conducted in this thesis assumes that there is equal land elsewhere in Auckland that can accommodate those displaced due to retirement of land. It also assumes that those displaced will accept such a decision. But considering benefit-cost results along with the potentially long duration of clean-up it is likely that some areas will need to be assigned lower priority for clean-up. Highest priority will be to re-establish important road segments running through impacted areas (e.g. Southern Motorway) followed by private properties. Of lowest priority will be public recreation spaces (e.g. parks, sports fields) which could be utilised as temporary storage sites for tephra before transportation to permanent disposal sites.

3.4.1.6 Model refinement and applications

This model could be refined by:

- testing the efficiency of different types of street sweepers at removing fine grained tephra deposits from road surfaces and under different conditions (e.g. wet or dry tephra deposits). Similar studies have been conducted in USA

(Selbig & Bannerman, 2007);

- an inventory of resources (e.g. disposal site capacity, truck type and number available, loaders available) available post-disaster;
- incorporating costs to establish disposal sites as this will influence cost-benefit of how many disposal sites should be utilised (e.g. one big site or many small sites);
- determining operational capacity and design of disposal sites (truck visits per day);
- modelling different eruption sizes and vent locations along a regularly spaced grid across Auckland which would allow determination of relative importance of eruption size and location. This would serve to demonstrate areas of vulnerability for eruption response and recovery planning across Auckland.

The model presented here has been designed to allow for easy integration and adaptation with other models. Examples are using clean-up durations in conjunction with economic impact models to better assess restoration of social and economic activities. This research has presented results in the form of zoning areas based on methods of clean-up. However, with some adaptation (e.g. incorporating prioritisation of land use type) it would be possible to model clean-up duration on a meshblock scale. Other factors such as risk to life, asset damage, and economic impacts to build up a picture of volcanic risk in Auckland, could also be incorporated

3.4.2 Implications for tephra clean-up in Auckland

This subsection discusses the implications this research has identified for response and recovery planning in Auckland following tephra fall and pyroclastic flow. First, implications for distal clean-up response is discussed. Then, discussion of proximal clean-up response planning. Finally, a discussion of implications for recovery planning after proximal eruptions is presented.

3.4.2.1 Distal clean-up response

Distal sourced tephra fall is likely to cause reductions in functionality of critical infrastructure such as transportation networks, water supply, waste-water, and electricity. The scenarios used in this thesis are unlikely to be sufficient to cause roof collapse, but can have a large impact on transportation, waste-water, water supply, and power systems. Additionally, fear of damage to vehicles and health concerns can led to individuals not venturing outside. These impacts result in major disruption of economic and social activities. This means that distal sourced tephra fall clean-up should be coordinated to prioritise reducing impacts to these services. Critical to this is to prevent tephra from entering the storm water system and preventing remobilisation.

Road networks are usually the first infrastructure to be impacted by tephra falls. Only 1 mm results in obscured road markings and reduced traction and visibility. This has led to increased incidence of traffic accidents and road closures elsewhere (Blong, 1984; Wilson et al., 2012). Therefore clean-up of road surfaces will be a priority after tephra fall. This might require road closures and parking restrictions to allow street sweepers to clean roads as efficiently and quickly as possible.

Distal sourced tephra fall deposits are likely to be very fine grained, and it will likely be necessary to stabilise dry deposits using water sprinkler trucks to prevent the tephra material from becoming airborne due to vehicle movements or by the wind. The methods used to clean road surfaces will depend on thickness of tephra fall deposits. For the 1 mm scenario street sweepers will be the most efficient way to remove tephra deposits. Whereas for the 10 mm scenario the use of graders first to pile tephra deposits at points where it will then be loaded onto trucks to be taken to disposal sites. After the bulk material has been removed by trucks, it will necessary for a street sweeping or water sprinkling operation to remove/stablise the residue.

For thin distal eruption scenarios, the volume of tephra material will be low at each property (<1 m^3). It is likely that residential property owners will be able to deal with such volumes on their own by adding it to gardens or letting it be absorbed into soil within grassed areas. Clean-up of inner city apartment buildings are likely to be able to be completed by maintenance workers or contracted cleaners. It might be necessary to distribute bags for collection of tephra deposits in some areas which might not have the means to add material to gardens.

For thicker deposits (>10 mm) clean-up of properties will need to be assisted by Auckland Council (or contractors) as the volumes will be too great for private property owners to cope. There are likely to be two options for managing such an operation: (1) distribute bags for property owners to fill and have them collected from the road side or designated pick-up points; (2) have all material moved on to roads and have graders push material into piles to be loaded onto trucks. The method chosen will depend on bag availability and planned methods of disposal.

3.4.2.2 Proximal eruption clean-up response and recovery

A proximal eruption is likely to result in an inhomogeneous spatial distribution of impacts. This is because areas closest to the vent will be heavily impacted by base surges and tephra fall, while areas further away will only have thin tephra impacts. This means that street sweepers, heavy earthmoving machinery, and volunteer workforce will all be required. Furthermore, there is likely to be an evacuation and exclusion zone which means some areas will not be cleaned until it becomes safe to do so. Resource and clean-up zone prioritising will be fundamentally important to the success of clean-up operation response.

In the immediate aftermath of a proximal eruption it will be critical that important transport corridors are as functional as possible to deal with emergency response situations. A Three Kings eruption scenario would be particularly problematic for this due to severe impacts on the Southern and Southwestern Motorways which would either be inside an evacuation zone or impacted by over 1 metre of tephra deposits. This makes it critical that roads outside an evacuation zone are as functional as possible to manage increased traffic loads due to road closures.

Appropriate disposal site location and design will be critical for efficient clean-up. A number of disposal sites (mostly public parks) have already been pre-identified as part of the Auckland Volcanic Field Contingency Plan, chosen largely because of their size and proximity to Auckland metropolitan area. It is possible that some of these sites will be not be appropriate for use in a proximal eruption scenario because of being located within exclusion zones. Additionally, some disposal sites might reach capacity before all material is removed. This suggests that larger sites might need to be established outside of the city, or marine disposal investigated in more detail. Most of the sites identified are public parks and are bordered by residential properties. Large numbers of trucks entering such areas could have a significant negative impact on the community due to traffic congestion and noise. In addition, noise and vibrations caused by heavy machinery use could negatively impact on residential areas and potentially breach requirements under NZS6803:P1999 Construction Noise Standards (Appendix 2). Therefore, it might be necessary to place restrictions on disposal site operation hours. This would serve to increase the time it takes to complete clean-up operations.

An other potential limiting factor on ability for an efficient and quick clean-up will be ready access to fuel and water supplies. Due to large areas of the city will be under an exclusion zone, access to fuel could be limited because of supplies lying within exclusion zones, being made inoperable due to tephra falls, base surges, and lava flows, or increased consumption due to inefficient routes of travel between pickup points and disposal sites. Water shortages have been experienced due to use for clean-up in past eruption clean-up operations. In a proximal eruption scenario, lava flows could set fire to structures raising the risk of out of control fires. For this reason, water supplies for clean-up purposes could be limited to ensure water resources are not depleted. This would increase the potential for remobilisation and prolonged clean-up.

As the eruption finishes or decreases in intensity, pressure could be applied to allow re-habitation of evacuated areas and begin recovery processes. There will be a number of challenges to be overcome before some of these areas can be re-habitated:

- cleaning and repair of roads to provide access;
- assessment of areas beyond repair;
- disposal of huge volumes of tephra deposits;
- separation and disposal of additional waste streams;

Before people can re-enter the evacuation zone, roads will need to be cleaned and restored. Some of these areas are likely to be heavily impacted due to impacts from base surges, ballistics, and lava flows. This could make access to some areas very difficult and prolong clean-up and restoration of this area. Some areas could be impacted beyond repair and so assessments will need to be conducted to prioritise areas which can be re-habited again.

In many of the areas impacted by base surges, ballistics, lava flows and heavy tephra fall there will also be other waste streams needing removal (e.g. damaged buildings, perishables, industrial chemicals). This will require a separation of wastes as there is potential for constituents within the debris such as perishables, asbestos or industrial chemicals that could be undesirable for clean-fill disposal. In the scenarios used within this thesis it is assumed that a successful and complete evacuation occurs, but there is also the possibility in a future AVF eruption that some people and animals could be killed. This would add another level of complexity and sensitivity to how and when clean-up operations are conducted.

If areas in heavily impacted areas are to be restored, tens of millions of cubic metres of material will to have to be removed. For context, approximately approximately, 3,000,000 m^3 of debris from New York City was sent to landfills across upstate New York and Pennsylvania following Hurricane Sandy (NYTimes, 2013). Clean-up of Three Kings sized eruptions could result in 10 times as much material requiring removal. Liquefaction clean-up in Christchurch resulted in about 500,000 metric tonnes of silt being disposed (Villemure, 2013). Clean-up from from a volcanic eruption in Auckland is likely to be on an unprecedented scale in New Zealand.

Chapter 4

Conclusions and recommendations

Sometimes the questions are complicated and the answers are simple.

Dr. Seuss (1904-1991)

4.1 Conclusions

The purpose of this thesis was to quantitatively assess potential tephra clean-up operations in Auckland and inform response planning. In order to met research objectives this thesis has systemically reviewed published and unpublished literature on tephra clean-up experiences and provides an evidence base for conducting tephra clean-up impact assessments and response planning. There appears to be a relationship where approximately 1% of low accumulation (1,000 m^3/km^2) tephra fall is removed compared to high accumulation tephra fall (100,000 m^3/km^2) where up to 80% is removed. An objective of this research was to review and analyse tephra clean-up operations to determine best approachs and potential challenges to tephra clean-up operations. A finding of this research is that a general common process to tephra clean-up operations exists, although globally variable approaches to clean-up and disposal strategies suggest local context (climate, land-use and community tolerance of residual tephra) is a key factor for tephra clean-up planning. Some communities have been able to quickly mobilise resources and clean-up large volumes of tephra in short periods of time. Other communities have faced considerable challenges and prolonged clean-up operations. Factors that contribute towards the variance in tephra clean-up experiences range from the physical characteristics of volcanic eruptions such as size of eruption and tephra fall grain size, to social characteristics such as previous experience or having clean-up plans. Planning and coordination of clean-up operations are identified as a priority for tephra fall risk management.

Having robust plans in place will assist with communities establishing lines of communication between stakeholders (e.g. city managers, contractors, property owners) and help determine resources required to restore functionality to facilities, reduce infrastructure and property damage, and limit human exposure to tephra.

The evidence base was used to inform a key thesis objective of conducting a deterministic impact assessment of Auckland. It particularly informed what surfaces need to be cleaned as part of a coordinated approach to clean-up and methodologies which should be undertaken. The estimated volumes of tephra needing to be removed fall in the range of a few tens of thousand cubic metres for a thin tephra fall from distal sources to tens of millions cubic metres for a large scale proximal eruption located in the middle of metropolitan Auckland. Clean-up of such volumes will be resource intensive, costly, and time consuming.

Clean-up in Auckland will range from approximately a month for a thin tephra fall deposit clean-up to potentially years to clean-up areas impacted by base surges. Costs range from millions of dollars for a thin tephra deposit clean-up to hundreds of millions of dollars to clean-up base surge impacted areas. Due to such time scales and costs for clean-up it will be very important that clean-up operations are conducted as efficiently as possible to facilitate disaster recovery.

Planning for clean-up in Auckland after volcanic eruptions should be a priority within disaster risk reduction measures. As part of robust planning for coordinated clean-up operations in Auckland after volcanic eruptions, high priority for areas clean-up operations need to be identified. These areas will likely be important transport corridors and city centres. Determining what the implications of an extended closure or reduced functionality of certain areas within Auckland (e.g. motorway system or CBD) would have on disaster response will help inform what resources will be needed to restore such areas in an acceptable time frame.

Finally, results from this thesis also provide lessons for other cities around the world that are at risk of volcanic activity. Tephra clean-up is complex and expensive which highlights the importance of having plans in place for the collection and disposal of tephra. The tephra clean-up model developed here is easily adaptable to many cities around the world to gain a more complete understanding towards tephra clean-up impacts.

4.2 Recommendations

This section details recommendations for future planning initiatives useful for volcanic eruption response planning, and research directions to assist with disaster risk reduction. General guidelines for planning for tephra clean-up in urban environments are presented, followed by specific recommendations for Auckland City, New Zealand. Finally, useful areas of future research are presented.

4.2.1 General guidelines for planning tephra clean-up in urban environments

Effective planning for tephra clean-up in urban environments requires:

- Tephra fall hazard estimation, including: tephra sources, expected tephra volume/unit area and tephra characteristics (e.g. grain size, mechanical strength, abrasiveness)
- Identification and prioritisation of land use zoning and roads for clean-up and quality of clean-up.
- Identification of tephra disposal sites and ideal tephra disposal site characteristics (e.g. size, road access, ownership, environmental considerations).
- An understanding of societal factors such as economical, environmental, public health and cultural values. These values will influence areas of prioritisation for clean-up, potential tephra disposal locations, and thoroughness of clean-up.
- Identification of resource requirements and development of mutual support arrangements.

4.2.2 Planning initiatives for Auckland

It is recommended that the feasibility of currently identified sites within the Auckland Volcanic Field Contingency Plan are reassessed to determine if these sites are still acceptable today. It is recommended that feasibility considers potential volumes which could be stored at each site. Further assessment of which sites would be acceptable for permanent disposal or temporary staging sites before transportation to a permanent site would also be beneficial.

Given the large volumes of tephra potentially requiring removal after proximal eruptions there is a possibility that land based disposal is not viable due to limits on land that is available for use as a disposal site. Therefore, assessing the potential for disposal into marine environments will be beneficial. An investigation into this would require assessing economic, environmental, legislative, and cultural impacts of such an activity.

There would be considerable value in investigating the possible re-use of tephra deposits. Tephra has been used as a resource around the world (e.g. aggregate in Indonesia, sand bags in Japan, grit on roads in Alaska). Large scale re-use of tephra after an eruption could help reduce the volume of tephra needing permanent disposal and potentially off-set clean-up costs by becoming a new revenue stream.

Building an inventory of clean-up resources availability in a post eruption scenario would be useful for determining capacity Auckland is capable to dealing a with post eruption crisis environment. It will also allow establishment of relationships between those parties involved in clean-up response management. Mutual support agreements between local or regional operators (e.g. mining operations) and Auckland Council would be useful for increasing resource capacity to deal with clean-up of large volumes of material.

4.2.3 Research directions

A number of research directions related to tephra clean-up which can contribute towards disaster risk reduction have been identified:

1. Costs associated with disaster clean-up operations are often uncertain, with many factors contributing to the total cost of clean-up. Further research to assess the relative importance of different factors (e.g. contractor costs, volunteer costs, vehicle maintenance costs, and disposal site establishment and running costs) contributing to clean-up cost would be beneficial.

2. It has been demonstrated that clean-up of areas impacted by base surges could potentially take years just to remove the large volumes of tephra. However, it is likely that buildings and infrastructure will be badly damaged, perhaps beyond repair. Therefore, a valuable contribution to disaster risk reduction would be enhanced understanding of the complexities involved with restoring areas that have been heavily impacted by pyroclastic flows, lahars, and lava flows. This includes:

    - the feasibility of removing volumes of material on such a scale;
    - determining waste generation as a result of building damage

3. This research has presented tephra clean-up operation results based on four potential eruption scenarios impacting Auckland. An approach where proximal and distal eruptions are modelled probabilistically would allow for identification of areas of high vulnerability based on tephra volumes to remove, clean-up duration and cost would a valuable contribution to volcanic risk assessment in Auckland.

4. A methodology to assess tephra clean-up volumes, duration and costs has been produced in this thesis. Expanding this work to other areas around New Zealand (such as Rotorua and New Plymouth) that are also at risk to volcanic eruptions would be beneficial for response planning and understanding potential impacts from a volcanic eruption.

5. This work has focussed on clean-up of tephra as a result of volcanic eruptions. Determining whether the lessons learned in this analysis, (e.g. scale of response and methods of clean-up) can be applied to other perils such as earthquakes, hurricanes, floods, or tsunami would be of benefit to disaster risk reduction.

References

ACEMG (2013) Auckland Volcanic Field Contingency Plan, Auckland Council, Auckland, 54p

Barnard, S.T., (2004) Results of a reconnaissance trip to Mt. Etna, Italy: The effects of the 2002 eruption of Etna on the province of Catania. *Bulletin of the New Zealand Society for Earthquake Engineering*, 37(2),pp.47-61

Baxter, P.J., Ing, R., Falk, H., Plikaytis, B., (1983) Mount St. Helens Eruptions: The Acute Respiratory Effects of Volcanic Ash in a North American Community. *Archives of Environmental Health*, 38(3), pp.138-43

Blong, R., (1984) *Volcanic hazards: a sourcebook on the effects of eruptions*, Academic Press, Australia, 424p

Blong, R., (2000) Volcanic hazards and risk management, *In Sigurdsson, H. et al., (2000) Encyclopedia of Volcanoes*, Academic Press, pp.1215-1227

Brown, C., Milke, M., Seville, E., (2011) Disaster waste management: A review article, *Waste Management* 31, pp.1085-1098

Brown, C., (2012) *Disaster Waste Management: a systems approach*, Unpublished doctoral thesis, University of Canterbury, Christchurch, New Zealand

Calvi, G.M., Pinho, R., Magenes, G., Brommer, J.J., Restrepo-Vlez, L.F., Crowley, H., (2006) Development of seismic vulnerability assessment methodologies over the past 30 years, ISET Journal of Earthquake Technology, 43(3), pp.75-105

Carey, S.N., Sigurdsson, H., (1982) Influence of particle aggregation on deposition of distal tephra from the May 18, 1980, eruption of Mount St. Helens Volcano. *Journal of Geophysical Research*, 87(B8), pp.70617072.

Casadevall, T.J., (1993) *Discussions and Recommendations from the Workshop on the Impacts of Volcanic Ash on Airport Facilities*, Seattle, Washington, April 26-28, 1993. U.S. Geological Survey, 54p

Civil Defence Emergency Mangement Act, No.33 (2002) retrieved on 9 December 2014 from http://www.legislation.govt.nz/act/public/2002/0033/latest/DLM149789.html

Clark, D.M., Lee, H., (1965) *Cenzia-arena clean-up in San Jose, Costa Rica: Operational aspects as related to nuclear weapon fallout decontamination.* Stanford Research Institute, Project MU-5069, 56p

De Blizal, E., Lavigne, F., Grancher, D., (2011) Quand lala devient la ressource: lactivit dextraction des matriaux volcaniques autour du volcan Merapi (Indonsie) dans la comprhension des risques locaux [When the hazard becomes the resource: block and sand mining around Merapi volcano (Indonesia) in risk studies] Cybergeo: *European Journal of Geography, Environment*, Nature, Paysage, 525

Department of Internal Affairs, (2008) National Civil Defence Emergency Management Strategy 2007, Department of Internal Affairs, Wellington, 16p

Dolan, L., Wilson, C., Johnston, D.M., (2003) Potential volcanic ash disposal sites, GNS Science Report 2003/75, 57p

Durand, M., Gordon, K., Johnston, D., Lorden, R., Poirot, T., Scott, J., Shephard, B., (2001) *Impacts of, and responses to ashfall in Kagoshima from Sakurajima Volcano - lessons for New Zealand*, Institute of Geological and Nuclear Sciences science report 2001/30, 53p

Edbrooke, S.W., Mazengarb, C., Stephenson, W., (2003) Geology and geological hazards of the Auckland urban area, New Zealand, *Quaternary International*, 103(1), pp.3-21

Federal Emergency Management Agency, (2009a) Multi-hazard Loss Estimation Methodology: Earthquake Model - Hazus MR4 User Manual, FEMA, 270p

Federal Emergency Management Agency, (2009b) Multi-hazard Loss Estimation Methodology: Hurricane Model - Hazus MR4 User Manual, FEMA, 270p

Federal Emergency Management Agency, (2009c) Multi-hazard Loss Estimation Methodology: Flood Model - Hazus MR4 User Manual, FEMA, 270p

Green, R.M., Bebbington, M.S., Cronin, S.J., Jones, G., (2014) Automated statistical matching of multiple tephra records exemplified using five long maar sequences younger than 75 ka, Auckland, New Zealand, *Quaternary Research*, 82(2), pp.405-419

Guffanti, M., Mayberry, G.C., Casadevall, T.J., Wunderman, R., (2009) Volcanic hazards to airports, *Natural Hazards*, 51(2), pp.287-302

Hayward, B.W., Murdoch, G.J., Maitland, G., Jaimieson, A., (2011), *Volcanoes of Auckland: the essential guide*, Auckland University Press, Auckland, New Zealand, 234p

Horwell, C.J., Baxter, P.J., (2006) The respiratory health hazards of volcanic ash: a review for volcanic risk mitigation. *Bulletin of Volcanology*, 69(1), pp.124

Hurst, T., Smith, W., (2004) A Monte Carlo methodology for modelling ashfall hazards, *Journal of Volcanology and Geothermal Research*, 138(3/4), pp.393-403

Hurst, T., Smith, W., (2010) Volcanic ashfall in New Zealand probabilistic hazard modelling for multiple sources, *New Zealand Journal of Geology and Geophysics*, 53(1), pp. 1-14

ISDR (2009) UNISDR Terminology on Disaster Risk Reduction, United Nations International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 30p

Ishimine, Y., Yoshida, H., Risk Management Department of Kagoshima City (2012) *Volcanic Ash Clean-up Operations in Kagoshima City*, IAVCEI 2013 Scientific Assembly, Kagoshima, Japan, July 20-24 2013, 4p

Japan Meteorological Agency (2013) *National Catalogue of the Active Volanoes in Japan (fourth edition, English version)*, Japan Meteorological Agency

Jenkins, S.F., Spence, R.J.S., Fonseca, J.F.B.D., Solidum, R.U., Wilson, T.M., (2014a) Volcanic risk assessment: Quantifying physical vulnerability in the built environment. *Journal of Volcanology and Geothermal Research*, 276, pp.105120

Jenkins, S.F., Wilson, T.M., Magill, C.R., Miller, V., Stewart, C., Marzocchi, W., Boulton, M., (2014b) *Volcanic ash fall hazard and risk: Technical Background Paper for the UN-ISDR 2015 Global Assessment Report on Disaster Risk Reduction*, Global Volcano Model and IAVCEI

Johnston, D.M., (1997) *The impact of recent falls of volcanic ash on public utilities in two communities in the United States of America*. Institute of Geological & Nuclear Sciences science report 97/5, 21p

Johnston, D.M., Nairn, I.A., Thordanson, T., Daly, M., (1997) *Volcanic Impact Assessment for the Auckland Volcanic Field*, Auckland Regional Council Technical Publications No. 79, 208p

Johnston, D.M., Houghton, B.F., Neall, V.E., Ronan, K.R., Paton, D., (2000) Impacts of the 1945 and 1995-1996 Ruapehu eruptions, New Zealand: An example of increasing societal vulnerability. *Geological Society of America bulletin*, 112(5), pp.720-726

Johnston, D.M., Becker, J., Alloway, B., Manville, V., (2001) *Auckland Engineering Lifelines Group Volcanic Ash Review Part 1, Impacts on Lifeline services and Collection/Disposal Issues*, Auckland Regional Council Technical Publication No.144, 50p

Johnston, D.M., Saunders, W., Killen, C., Glavocic, B., Dolan, L., Van Schalkwyk, R., Cousins, J., Brown, C., McIntyre, I., (2009) *Disposal of debris following urban earthquakes: Guiding the development of comprehensive pre-event plans*, GNS Science Report 2009/33 30p

Kagoshima City, (2013) *Overview of measures against Sakurajima Volcano*, Kagoshima City, 223p

Kartez, J.D., Kelley, W.J., (1980) *Emergency planning and the adaptive local response to the Mt. St. Helens eruption*. Pullman, WA: Washington State University, Program in Environmental Science & Regional Planning, Environmental Research Center, 100p

Kereszturi, G., Nemeth, K., Cronin, S.J., Agustin-Flores, J., Smith, I.E.M., Lindsay, J., (2013) A model for calculating eruptive volumes for monogenetic volcanoes Implication for the Quaternary Auckland Volcanic Field, New Zealand, *Journal of Volcanology and Geothermal Research*, 266, pp.16-33

Kereszturi, G., Nemeth, K., Cronin, S.J., Procter, J., Agustin-Flores, J., (2014) Influences on the variability of eruption sequences and style transitions in the Auckland Volcanic Field, New Zealand, Journal of Volcanology and Geothermal Research, 286, pp.101-115

Kermode, L., (1992) *Geology of the Auckland Urban Area*, Scale 1:50 000, Institute of Geological and Nuclear Sciences Limited, Lower Hutt, New Zealand

Kidwell-Ross, R., Sutherland, R. (2010). An Overview of U.S. Sweeping Equipment and Technology. Retrieved on February 17 2014 from http://www.worldsweeper.com/ChooseEquipment/pdf/ ExplanationOfSwprTypes12.2010.pdf

Leonard, G.S., Williams, S., Finnis, K., Johnston, D., Cole, J.W., Barnard, S., (2005) *Impacts and management of recent volcanic eruptions in Ecuador: lessons for New Zealand*, GNS Science Report 2005/20, 52p

Lindsay, J., Marzocchi, W., Jolly, G., Constantinescu, R., Selva, J., Sandri, L., (2010) Towards real-time eruption forecasting in the Auckland Volcanic Field: application of BET_EF during the New Zealand National Disaster Exercise 'Ruaumoko', *Bulletin of Volcanology*, 72(2), pp.185-204

Lombardo, D., Ciancio, N., Campisi, R., Maria, A.D., Bivona, L., Poletti, V., Mistretta, A., Biggeri, A., Maria, G.D., (2013) A retrospective study on acute health effects due to volcanic ash accumulation during the eruption of Mount Etna (Sicily) in 2002. *Multidisciplinary Respiratory Medicine*, 8(1), 51p

Magill, C., Blong, R., Mcaneney, J., (2006) VolcaNZ A volcanic loss model for Auckland, New Zealand. *Journal of Volcanology and Geothermal Research*, 149(3-4), pp.329-345

Magill, C., Wilson, T., Okada, T., (2013) Observations of tephra fall impacts from the 2011 Shinmoedake eruption, Japan. *Earth Planets Space*, 65, pp.677-698

McLucas, G.B., (1980) Cleanup and disposal of Mount St. Helens ash in eastern Washington. *Washington Geologic Newsletter*, 8(4), pp.1-7

Miyabuchi, Y., Hanada, D., Niimi, H., Kobayashi, T., (2013) Stratigraphy, grain-size and component characteristics of the 2011 Shinmoedake eruption deposits, Kirishima Volcano, Japan. *Journal of Volcanology and Geothermal Research*, 258, pp.31-46

Moore, L.C., The distal terrestrial record of explosive rhyolitic volcanism: an example from Auckland, New Zealand, Sedimentary Geology, 74(1-4), pp.25-38

Morgan, A.V., (2000) The Eldfell Eruption, Heimaey, Iceland: A 25 Year Retrospective, *Geoscience Canada*, 27(1), pp.11-18

Naranjo, J.A., Moreno, H., Banks, N., (1993) La erupcion del volcan Hudson en 1991 (46S), region XI, Aisen, Chile, Sernageomin, Santiago, pp.44-50

NYTimes, (2013) *Cleanup from Hurricane Sandy is a Military-Style Operation*, Retrieved 1 November 2014 from http://www.nytimes.com/2012/11/17/nyregion/cleanup-from-hurricane-sandy-is-military-style-operation.html

Oze, C., Cole, J., Scott, A., Wilson, T.M., Wilson, G., Gaw, S., Li, Z., (2013) Corrosion of metal roof materials related to volcanic ash interactions, *Natural Hazards*, 71(1), pp.785802

Parfitt, L., Wilson, L., (2009) Fundamentals of Physical Volcanology, Wiley, 256p

Paton, D., Johnston, D., Gough, J., Dowrick, D., Manville, V., Daly, M., Batistich, T., Baddon, L., (1999) *Auckland Volcanic Risk Project: Stage 2*, Auckland Regional Council Technical Publication Number 126, 99p

Peurifoy, R., Schexnayder, C.J., (2002) *Construction Planning, Equipment, and Methods*, Sixth Edition, Boston, McGaw-Hill, 660p

Reinhart, D.R., McCreanor, P.T., (1999) Disaster Debris Management Planning Tools, retrieved 12 August 2014 from http://www.cece.ucf.edu/people/reinhart/research/ddfinalreport.pdf

Sarna-Wojcicki, A.M., Shipley, S., Waitt, R.B., Dzurisin, D., Wood, S.H., (1981) *Areal distribution, thickness, mass, volume, and grain size of air-fall ash from six major eruptions of 1980*, in Lipman, P.W., Mullineaux, D.R. (Eds.), The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, pp.577-600

Schilling, J.G., (2005) *Street Sweeping - Report No. 1, State of the Practice, Ramsey-Washington Metro Watershed District*, North St. Paul, Minnesota, 39p

Schuster, R.L., (1981) *Effects of eruptions on civil works and operations in the Pacific Northwest.* In P. W. Lipman, D. R. Mullineuax (Eds.), The 1980 eruptions of Mount St. Helens, Washington, U.S. Geological Survey Professional Paper 1250, pp.701-718

Selbig, W.R., Bannerman, R.T., (2007), *Evaluation of Street Sweeping as a Stormwater-Quality-Management Tool in Three Residential Basins in Madison, Wisconsin*, U.S. Geological Survey Scientific Investigations Report 20075156, 103 p.

Self, S., Sparks, R.S.J., Booth, B., Walker, G.P.L., (1974) The 1973 Heimaey Strombolian Scoria deposit, Iceland. *Geological Magazine*, 111(6), pp.539-548

Shane, P., Hoverd, J., (2002) Distal record of multi-sourced tephra in Onepoto Basin, Auckland, New Zealand: implications for volcanic chronology, frequency and hazards, *Bulletin of Volcanology* 64, pp.441-454.

Shulters, M.V., Clifton, D.G., (1981) *Mount St. Helens Volcanic-Ash Fall in the Bull Run Watershed, Oregon, March - June 1980*, Geological Survey Circular 850-A, 23p

Sneva, F.A., Britton, C.M., Mayland, H.F., Buckhouse, J., Evans, R.A., Young, J.A., Vavra, M., (1982) *Mt. St. Helens Ash - Considerations of its fallout on rangelands: Corvallis Oregan*, Oregan State University Agricultural Experiment Station Special Report 650, 27p

Spence, R.J.S., Kelman, I., Baxter, P.J., Zuccaro, G., Petrazzuoli, S., (2005) Residential building and occupant vulnerability to tephra fall. *Natural Hazards And Earth System Sciences*, 5(4), pp.477-494

Standards New Zealand (2009) Risk Management - principles and guideline (AS/NZS ISO 31000:2009)

Statistics New Zealand, (2014a) *QuickStats about Auckland Region*, retrieved 15 October 2014 from http://stats.govt.nz/Census/2006CensusHomePage/QuickStats/AboutAPlace/SnapShot.aspx?id=1000002&type=region&ParentID=

Statistics New Zealand, (2014b) *Regional Gross Domestic Profit: Year ended March 2013*, retrieved 15 October 2014 from http://www.stats.govt.nz/browse_for_stats/economic_indicators/NationalAccounts/RegionalGDP_MRYeMar13.aspx

Statistics New Zealand., (2014c) *2013 Census meshblock dataset*, retrieved 12 August 2014 from http://www.stats.govt.nz/Census/2013-census/data-tables/meshblock-dataset.aspx

Sutherland, R., Kidwell-Ross, R., (2010) *10 Tips for Ensuring a More Environmental and Cost-Effective Street Sweeping Program*, Retrieved on 01/09/2014 from http://www.worldsweeper.com/Street/BestPractices/Sutherland10Tips10.10.html

Sword-Daniels, V., Wilson, T.M., Sargeant, S., Rossetto, T., Twigg, J., Johnston, D.M., Loughlin S.C., Cole, P.D., (2014) Consequences of long-term volcanic activity for essential services in Montserrat: challenges, adaptations and resilience. *Memoir of the Geological Society of London Special volume "The Eruption of Soufriere Hills Volcano, Montserrat from 2000-2010*

Teramoto, Y., Shimokawa, E., (2011) Effect of volcanic activity on physical properties of volcanic ash on the hillside slope of Mount Sakurajima. *Journal* *of the Japanese Society of Coastal Forest*, 10(1), pp.1-5

Villemure, M., Wilson, T.M., Bristow, D., Gallagher, M., Giovinazzi, S. and Brown, C. (2012) *Liquefaction ejecta clean-up in Christchurch during the 2010-2011 earthquake sequence*. University of Canterbury, Christchurch, New Zealand: New Zealand Society for Earthquake Engineering: 2012 Annual Technical Conference (NZSEE), 13-15 Apr 2012.

Villemure, M., (2013) *Fine grained sediment clean-up in a modern urban environment*, Unpublished master's thesis, University of Canterbury, Christchurch, New Zealand

Wallace, K.L., Schaefer, J.R., Coombs, M.L., (2013) Character, mass, distribution, and origin of tephra-fall deposits from the 2009 eruption of Redoubt Volcano , Alaska Highlighting the significance of particle aggregation. *Journal of Volcanology and Geothermal Research*, 259, pp.145-169

Wang, H., Wang, G., Wang, F., Sassa, K., Chen, Y., (2008) Probabilistic modeling of seismically triggered landslides using Monte Carlo simulations, *Landslides*, 5(4), pp.387-395

Wardman, J., Sword-Daniels, V., Stewart, C., Wilson, T.M. (2012) *Impact assessment of the May 2010 eruption of Pacaya volcano, Guatemala*, GNS Science Report 2012/09, 90p

Warrick, R.A., Anderson, J., Downing, T., Lyons, J., Ressler, J., Warrick, M., Warrick, T., (1981) *Four communities under ash - after Mount St. Helens.* Program on Technology, Environment and Man, Monograph 34, Institute of Behavioural Sciences, University of Colorado, 148p

Williams, R.S., Moore, J.G., (1983) *Man Against Volcano : The Eruption on Heimaey, Vestmannaeyjar, Iceland*, U.S. Geological Survey, 31p

Wilson, T.M., Cole, J.W., Johnston, D.M., Stewart, C., Dewar, D.J., Cronin, S.J., (2009) *The 1991 eruption of Volcan Hudson, Chile: impacts on agriculture and rural communities and long-term recovery*, GNS Science Report 2009/66, 99p

Wilson, T.M., Cole, J.W., Stewart, C., Cronin, S.J., (2011) Ash storms: impacts of wind-remobilised volcanic ash on rural communities and agriculture following the 1991 Hudson eruption, southern Patagonia, Chile. *Bulletin of Volcanology*, 73, pp.223-239

Wilson, T.M., Stewart, C., Sword-Daniels, V., Leonard, G.S., Johnston, D.M., Cole, J.W., Wardman, J., Wilson, G., Barnard, S.T., (2012) Volcanic ash impacts on critical infrastructure. *Physics and Chemistry of the Earth*, 45-46, pp.5-23

Wilson, T.M., Outes, V., Stewart, C., Villarosa, G., Bickerton, H., Rovere, E., Baxter, P., (2013) *Impacts of the June 2011 Puyehue-Cordn Caulle volcanic complex eruption on urban infrastructure, agriculture and public health.* GNS Science Report 2012/20, 88p

Wilson, G., Wilson, T.W., Deligne, N.I., Cole, J.W., (2014) Volcanic hazard impacts to critical infrastructure: A review, *Journal of Volcanology and Geothermal Research*, 286, pp.148-182

Yu, J.J., Qin, S.X., Larsen, O., (2013) Joint Monte Carlo and possibilistic simulation for flood damage assessment, *Stochastic Environmental Research and Risk Assessment*, 27(3), pp.725-735

Zais, D., (2001) *Managing the Mt. St. Helens Volcanic Ashfall on Yakima, Washington, U.S.A.* Retrieved 2 February 2014 from http://volcanoes.usgs.gov/ash/dickzais.html

Appendix 1 - Street sweeper classifications

Mechanical broom sweepers

Mechanical broom sweepers have been reported as only used for aesthetic reasons and largely inadequate at sweeping for environmental purposes. This is because the action of the sweeper breaks larger grain sizes to smaller grain sizes which the conveyor system has trouble transporting to the hopper and in effect leaves the smaller grain sizes on the road surface (Kidwell-Ross & Sutherland, 2010).

Figure 1: Mechanical broom sweeper (image: Elgin)

Regenerative air sweepers

A regenerative air sweeper works by blasting air on to the road surface opposite to the pickup tube. The air travels across the width of the head picking up grains, and is then sucked up the pickup tube on the other side. Because they blast the road surface across the width of the unit, they are more effective at cleaning a larger area than vacuum sweepers (Kidwell-Ross & Sutherland, 2010).

Figure 2: Regenerative air sweeper (image: Elgin)

Vacuum sweepers

A fundamental difference between vacuum and regenerative air sweepers is that vacuum sweepers are constantly exhausting the air during sweepers. As opposed to regenerative air sweepers which employ an air blasting methodology to move grains towards the intake, a vacuum sweeper works by brooming grains from the road surface towards the air intake tube which then sucks the grains up into the system. For this reason, vacuum sweepers are not as effective at cleaning whole lanes as regenerative air sweepers(Kidwell-Ross & Sutherland, 2010).

Figure 3: Vacuum sweeper (image: Elgin)

Appendix 2 - New Zealand Standard NZS6803:P1999 Construction Noise Standards

Table 1 indicates that a buffer of more than 10 m will be required in residential areas to fall within the requirements of NZS6803:P1999. Noise from machinery used at sites is likely to be close to the limit for short term works (less than 2 weeks), and to exceed day limits for longer works at a distance of 10 m from machinery. The noise effects on neighbours could be mitigated by keeping a buffer zone of greater than 10 m between the site neighbours and any machinery. Additionally, site hoardings can be useful both for physical and psychological reasons by removing the direct line of sight between the source and the listener. Therefore, designing of hoardings should take this into consideration.

Table 1: Noise levels as approximated for Burwood Resource Recovery Park machinery, and NZS 6803 standards. Short term = 14 calendar days, typical duration = More than 14 calendar days but less than 20 weeks, long duration = Greater than 20 weeks. Day = 0730-1800, Night = 1800-2000

Machinery	**Maximum noise at 10 m distance (dBA)**	**NZS 6803 Construction Noise Standard dBA**					
		Short term		**Typical duration**		**Long duration**	
		Day	Night	Day	Night	Day	Night
Dump truck	78	80	75	75	70	70	65
Water tanker	80						
Fuel tanker	80						
Light vehicles	80						

Appendix 3 - Monte Carlo modelling spreadsheets

See accompanying media

Appendix 4 - GIS data

See accompanying media